SIM
SISTEMA INTERAMERICANO DE METROLOGÍA

SIM METROLOGY SCHOOL

MWG 4\ CCL Length

SPEAKER

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(NIST – Gaithersburg, MD campus)

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NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Introduction

Cubit – the tool of ancient and medieval societies

Cubit Museo Egizio, CC0, via Wikimedia Commons (attribution not legally required)

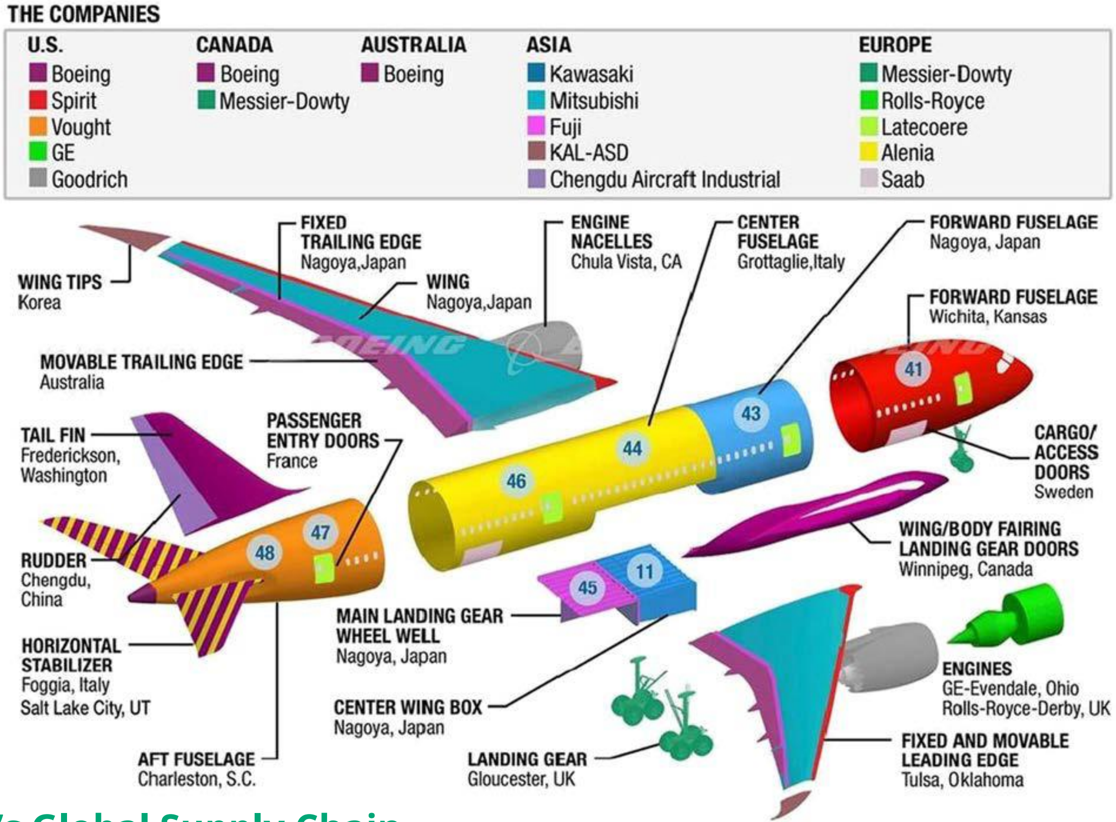
Introduction

Great Pyramid of Giza

Great Pyramid of Giza was constructed with sides that are 440 cubits (appr. 230 meters) in length.
The Pyramid was within 11.4 cm of the designed dimensions– accuracy better than 0.05%.

Introduction

Distributed supply chains require a common system of length



Boeing's Global Supply Chain
Source: the Boeing Company

Historical Evolution of the SI unit of length

Historical Evolution of length measurements

Realization of the SI meter (looking back in history)

1983 – Present The length of the meter was defined as the distance traveled by light in a vacuum in 1/299,792,458 seconds.

1960 – 1983 11th CGPM definition of the meter as the length equal to 1,650,763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p^{10}$ and $5d^{5}$ of the krypton-86 atom.

1889 – 1983 International prototype meter (IPM) – line standard.

1799- 1889 platinum iridium meter of the archives bar in Paris. – end standard.

Provision meter based on the Toise of Peru

Historical Evolution of length measurements

History of the original SI meter

During the French revolution there was interests in developing a global system of units.

Internal units of length and mass varied from state to state and sometimes from parish to parish.

Expansion of trade with the colonies in the Americas also meant that a global system of units would be beneficial by ensuring fairness and equity in these growing avenues of trade. (That is, at least for the free people.)

There were multiple alternatives. For establishing the unit, to replace the French toise (approximately 1.95 m)

Historical Evolution of length measurements

History of the original SI meter

One choice was to define the length in terms of a pendulum. That is, it would be accessible to anyone, anywhere in the world. Although, even during this time scientist knew the length would be dependent on the latitude because of the variation of local gravity.

Another choice was to use a fraction of the circumference of the earth. Specifically , the length was selected to be 1/10,000,000 of the length of the meridian from the north pole to the equator and passing through Paris. Because meridians were believed to be all the same length, this definition would be accessible for all people for all time. (that is, for free people)

Further, the meridian was also convenient because the length was approximately equal to the French aune, which would have been about 119 centimeters. A practical length.

Historical Evolution of length measurements

History of the original SI meter

Jean-Baptiste-Joseph Delombre

Pierre-Francois Andre Mechain

Two French astronomers were selected to perform the measurement of the meridian.

Measurement from the north pole to the equator was not practical so it was decided that they would measure portion of the meridian from Dunkirk in the North to Barcelona in the south and passing through Paris.

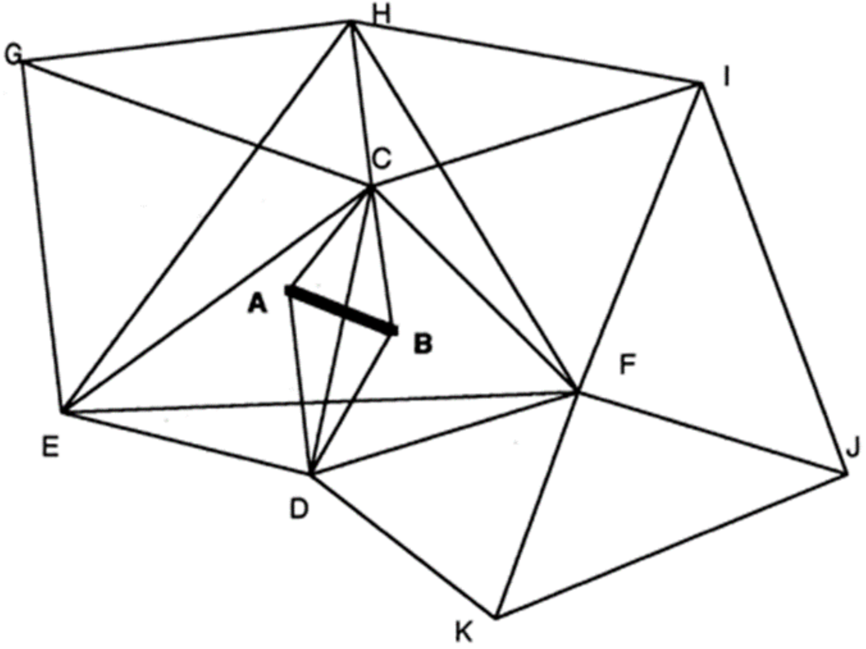
Historical Evolution of length measurements

History of the original SI meter

Triangulation networks were used by geodetic surveyors and cartographers since the 1600s when Jean Picard used the first surveyor's angle instrument with crosshairs on the telescope. Modern triangulation methods is based on work by Willebrord Snell. (Early 1600s)

Triangulation using AB as a base line The distance AB is measured precisely Then C, D, E, F, G, H, I, J and K can be fixed by angular measurement only.

The base line was measured using a scale. At the time the post common scale was the toise of Peru.



Historical Evolution of length measurements

History of the original SI meter

Why weren't existing surveys used to estimate the ¼ meridians length. Maps of France existed at the time of the proposed survey. The Cassini family, for four generations had done extensive maps of France from the late 1600s into the 1800s.

Giovanni Domenico Cassini
Jean-Dominique Cassini
1625-1712

Jacques Cassini
1677-1756

Cesar-Francois Cassini
De Thury
1714-1784

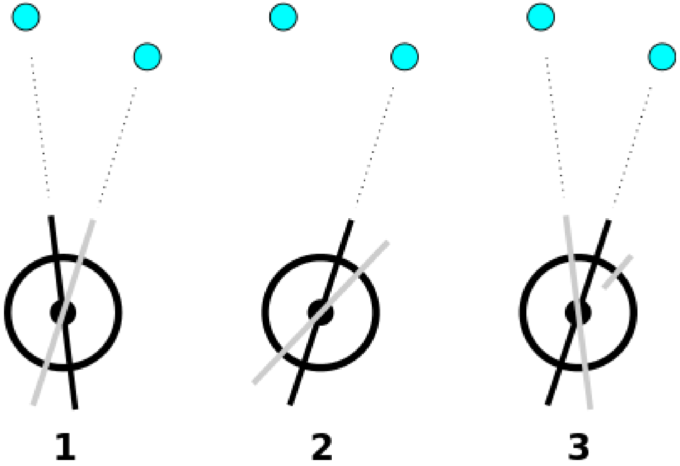
Jean-Dominique
comte de Cassini
1748 – 1845)

Historical Evolution of length measurements

History of the original SI meter

Borda Repeating circle

Daderot, Public domain, via Wikimedia Commons



https://scientificgems.wordpress.com/2013/06/03/dunkerque-to-barcelona-in-metres-a-review-of-the-measure-of-all-things/

Historical Evolution of length measurements

History of the original SI meter

Events during the Survey of the Meridian to define the meter from 1792-1799

- Delambre – arrested on occasions
- Delambre – fired from survey
- Delambre – faced periodic struggles from locals who thought he was a sorcerer and believed his instruments would bring the plague to their village.
- Mechain – Stranded in Barcelona
- Mechain – Injured and stranded in Barcelona
- Mechain – error in Barcelona haunts him till death
- Meter of the Archives defined from “analyzed data set”
- Everybody gets medals and requisite praise.
- Mechain returns to Barcelona, dies of malaria

https://scientificgems.wordpress.com/2013/06/03/dunkerque-to-barcelona-in-metres-a-review-of-the-measure-of-all-things/

Historical Evolution of length measurements

History of the original SI meter

Consequences of the Survey of the Meridian to define the meter from 1792-1799

- Discovered the earth is lot more irregular and simply was not a suitable artifact, “for all people for all time”
- Because of the irregularities of the earth extrapolation from the small survey to the length of the quarter meridian would have been fraught with error.
- Lack of understanding between precision and accuracy, and the lack of statistical tools made the analysis problematic.
- Legendre successfully employed, what he thought was a new method of least squares to analyze the errors and determine the goodness of fit, however, Gauss took issue with Legendre’s use of the term “new method”.

Historical Evolution of length measurements

History of the original SI meter

Consequences of the Survey of the Meridian to define the meter from 1792-1799

- In 1799, the world scientific community gathered in France to review all the data and arrive at the value for the length of a meter in terms of the toise.
- This new value included data from a 50 years earlier that extended all the way to the equator to get a better approximation of curvature of the earth.
- The estimate was calculated from these data and a platinum standard produced that was the accepted value in length of 443.296 lignes. **The meter of the archives**, which replaced the existing provision meter that was developed by Borda.

Historical Evolution of length measurements

History of the SI meter

- The meter of the Archive was constructed of pure platinum with parallel surface at each end.
- It was constructed so that its ends were 443.296 lignes apart.
- 20 bars were built and the one closest to the 443.296 lignes was selected as the meter of the archives and placed in the French National Archives

Historical Evolution of length measurements

The Second International Conference for the Measurement of Degrees in Europe – Berlin 1867.

Consequence of this meeting

Needed better access to the meter of the archives

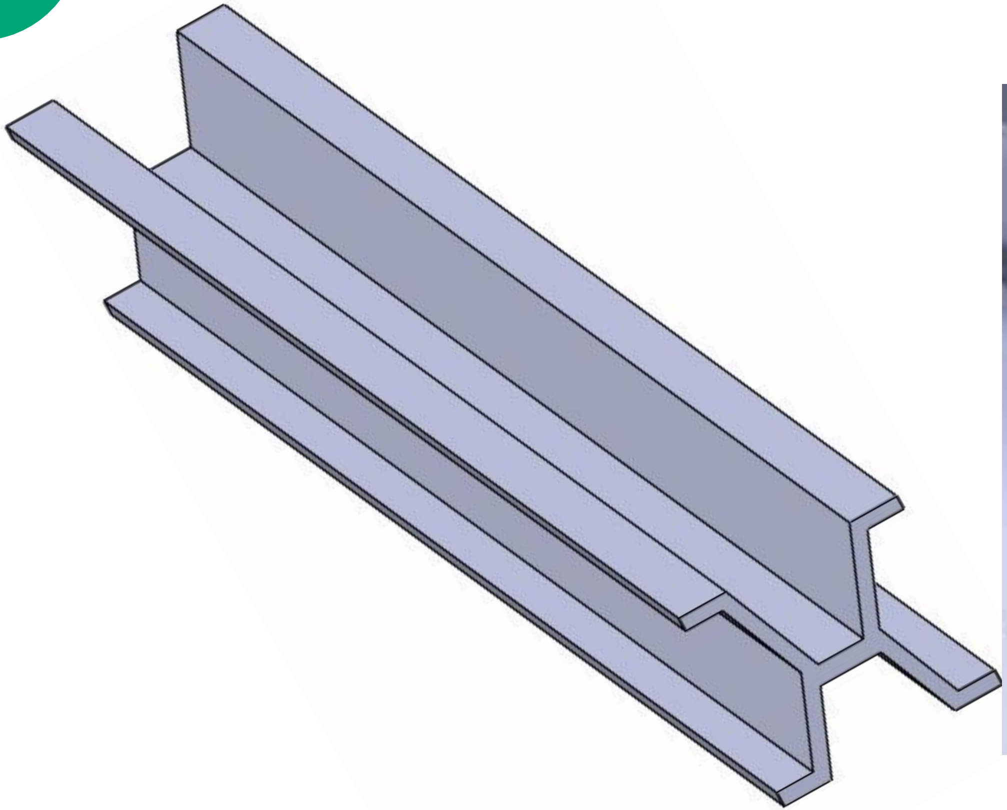
Change the meter of the archive from an end standard to a line standard

French created an international meter commission to discuss these recommendations. Meetings took place in 1870 and 1872. They established the Diplomatic Conference of the Meter held in Paris in 1875.

Decided to make a new prototype meter, a line standard, that replaced the meter of the archives.

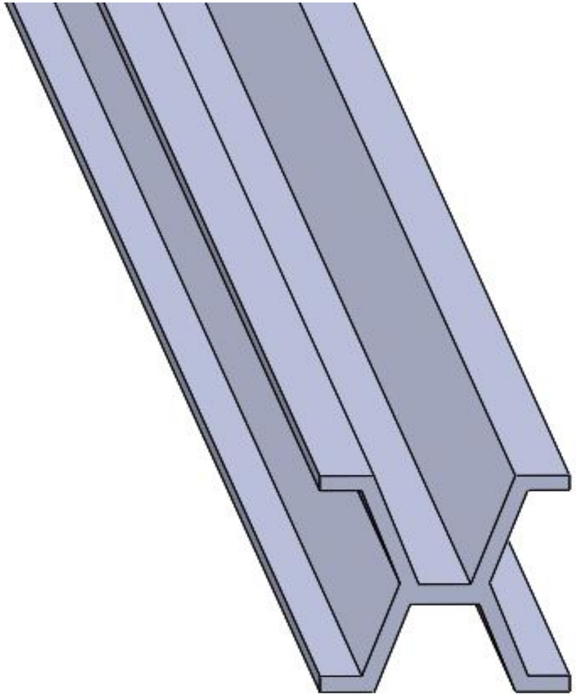
Historical Evolution of length measurements

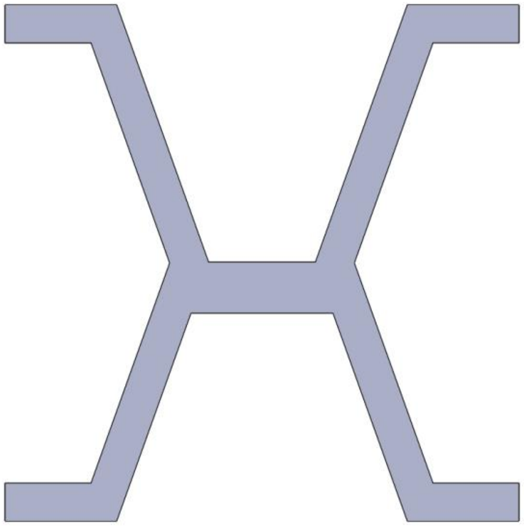
From an end standard to a line standard.



Historical Evolution of length measurements

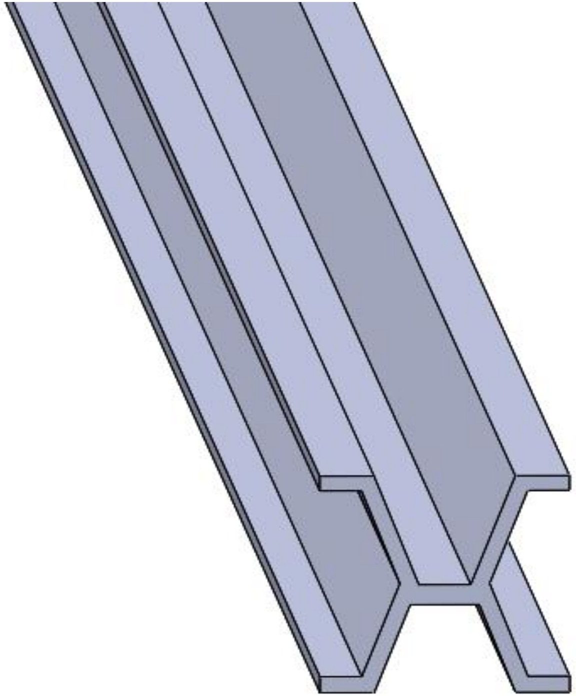
From an end standard to a line standard.

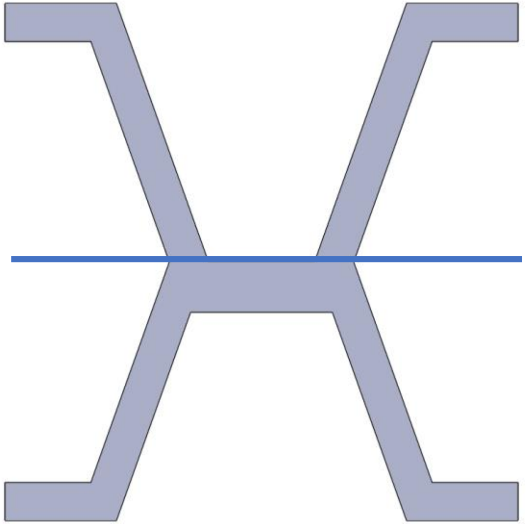




Historical Evolution of length measurements

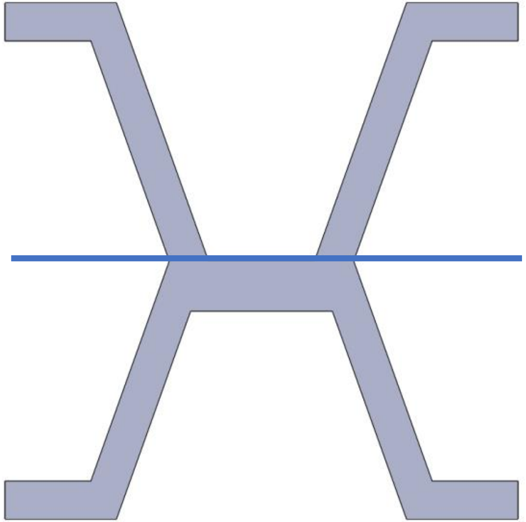
From an end standard to a line standard.





Historical Evolution of length measurements

From an end standard to a line standard.



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Provision meter based on the Toise of Peru

Basic Measurement Principles

Basic Measurement Principles

JCGM 200:2012 International vocabulary of metrology

2.4 (2.3)

measurement principle

principle of measurement

phenomenon serving as a basis of a measurement

- EXAMPLE 1 Thermoelectric effect applied to the measurement of temperature.
- EXAMPLE 2 Energy absorption applied to the measurement of amount-of-substance concentration.
- EXAMPLE 3 Lowering of the concentration of glucose in blood in a fasting rabbit applied to the measurement of insulin concentration in a preparation.

NOTE The phenomenon can be of a physical, chemical,
or biological nature.

Basic Measurement Principles

JCGM 200:2012 International vocabulary of metrology

NMIs typically realize the SI meter through laser interferometry using optical frequencies.

We also use an array of master gages, which are traceable to the SI unit of length through interferometry.

I will discuss the principles of measurement for material reference and optical interferometry separately.

Basic Measurement Principles

Artifact base reference lengths

The length of an object depends on its temperature

- When things get hotter, most materials grow
- When things get colder, most materials shrink.

Consequently, to help create an unambiguous length, international standards establish a reference temperature, at which, length is defined. Currently, the reference temperature for geometric product specification is 20 ° C. ISO 1

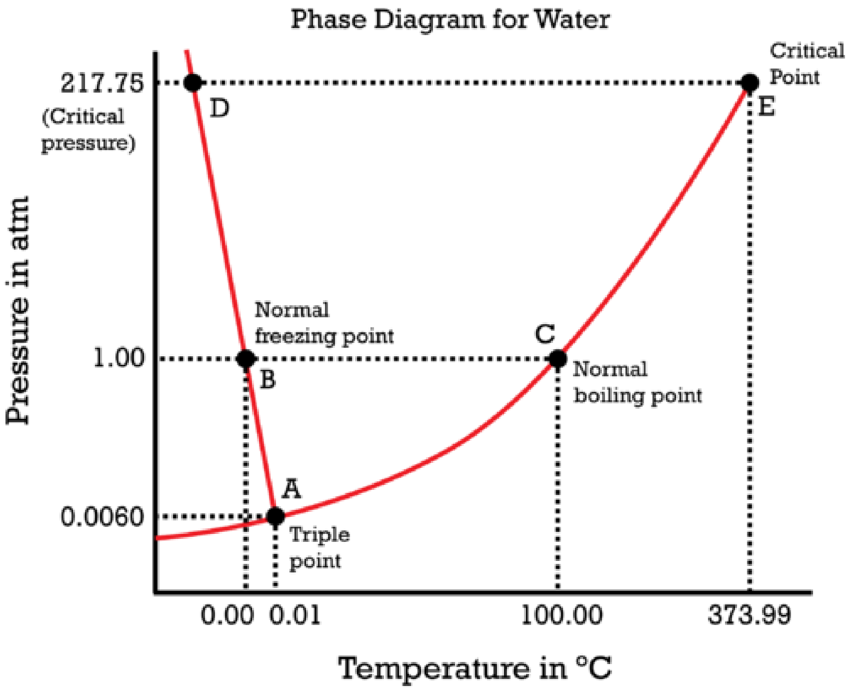
Excerpt from ISO 1

Section 3. Standard reference temperature value for the specification of geometrical and dimensional properties

The standard reference temperature value for the specification of geometrical and dimensional properties shall be fixed at 20 °C. Unless otherwise explicitly specified, the reference temperature for geometrical and dimensional properties of workpieces shall be the standard reference temperature.

Basic Measurement Principles

Artifact based reference lengths - temperature



*20 ° C – A Short History of the Standard Reference Temperature for Industrial Dimensional Measurements

Basic Measurement Principles

Artifact based reference – fixturing/support

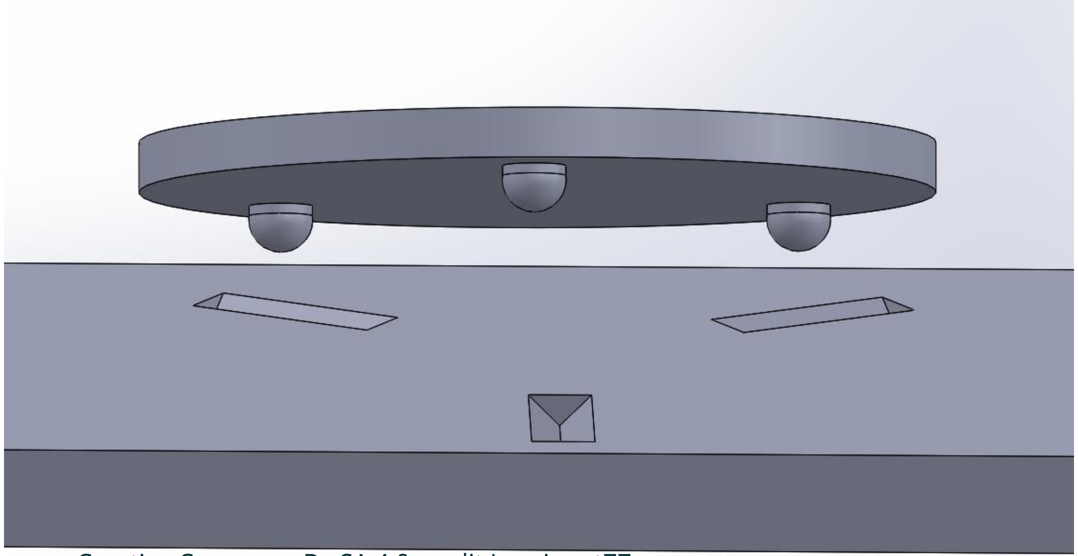
- Fixtures and support must not over constrain the artifact. We refer to this as a non-influencing support. Induced stress caused by clamping will change the value of the reference length.

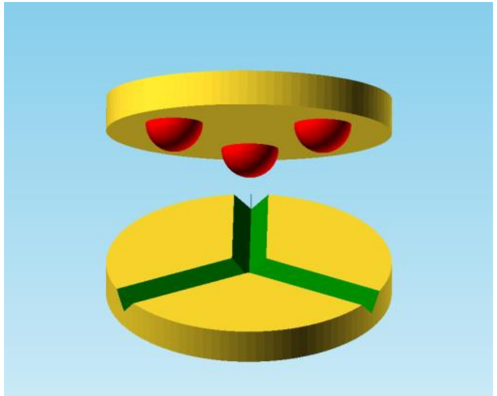
- Kinematic analysis is performed when designing or fixturing a reference artifact. The degrees of freedom constrained by each contact point with the gauge must be consider when designing fixturing. Also, the effect of gravity must be considered if the gauge is to be reoriented within the work volume during calibration of a system.

Basic Measurement Principles

Artifact based reference length – fixturing/support

Maxwell Clamp - In this instance gravity is employed as a clamping force. All rigid body degrees of freedom are constrained.





Red hemispheres attached to the bottom of a diameter standard. 3 V grooves are show in green.

Uniform growth due to temperature changes is about the center of the plug gage.

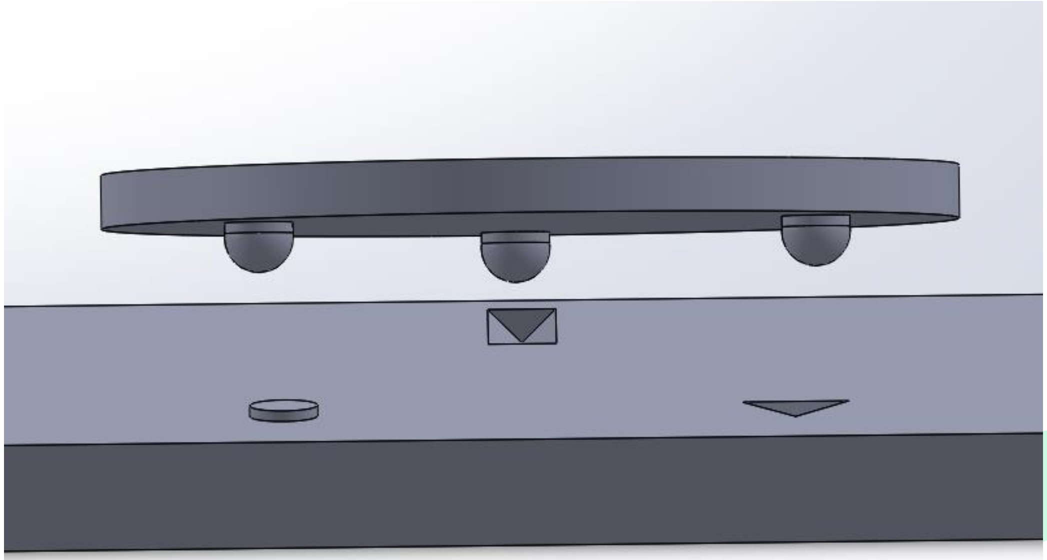
Basic Measurement Principles

Artifact based reference length – fixturing/support

Kelvin Clamp - Gravity is employed as a clamping force. But clamping force can be applied to the plate over the hemisphere positioned in the cone

Hemisphere in a cone constrains 3 translations. The hemisphere in the V-groove constrains 2 rotations. The final, flat controls 1 rotational degree of freedom.

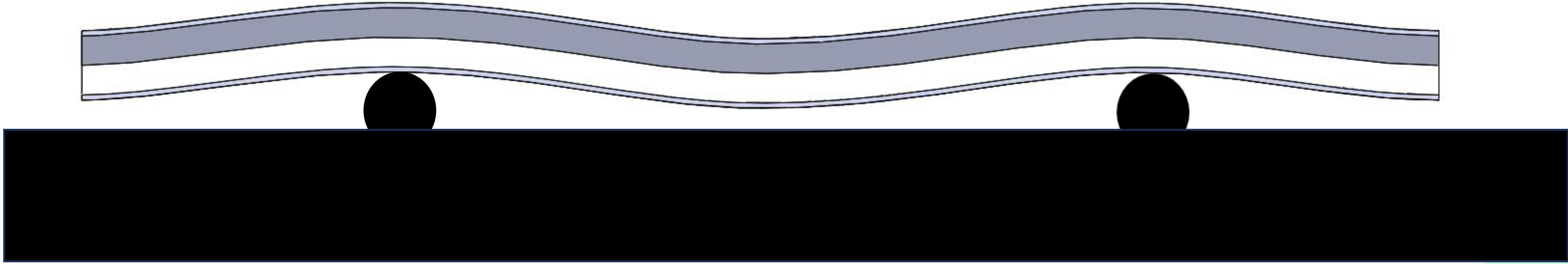
Expansion



Basic Measurement Principles

Artifact based reference length - deformation

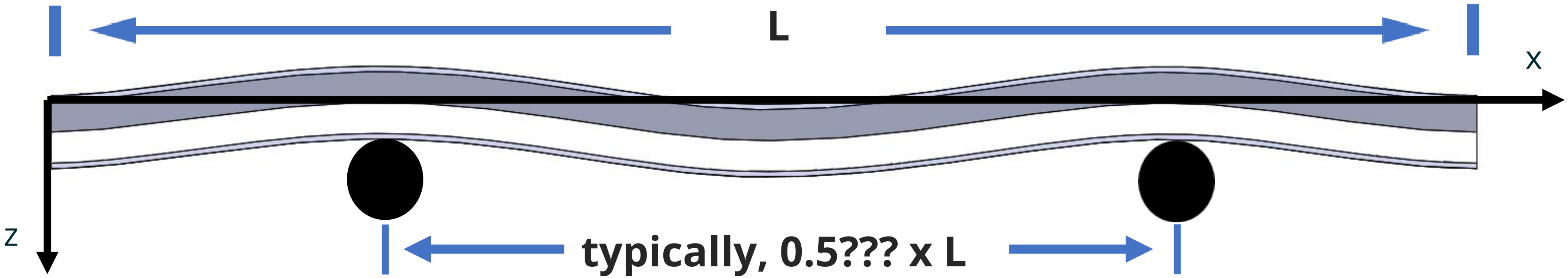
Prismatic reference artifacts, the meter of the archive for instance, is supported on hardened polished cylinders which are typically truncated and mounted on a flat surface. The shape of the beam illustrates the affects of gravity on a long slender beam support as described. The deflections are exaggerated.



Basic Measurement Principles

Artifact based reference length-fixturing line standards

Line standards are supported on the Bessel Points. These are the points that maximizes the overall length due to bending, or equivalently the deflection of the beam, due to gravity, is minimized.



Basic Measurement Principles

Artifact based reference length-fixturing line standards

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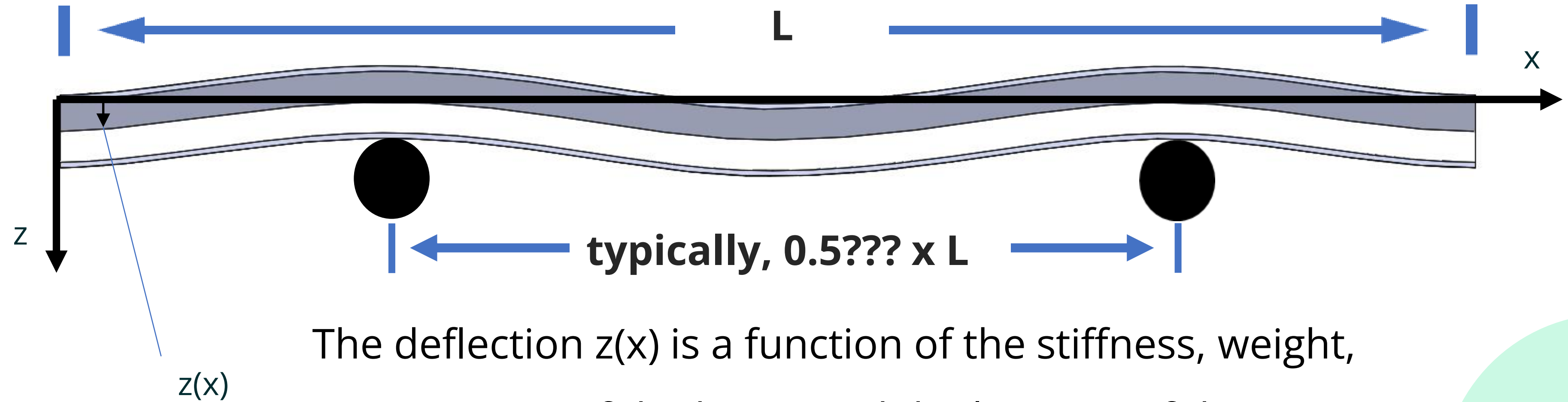
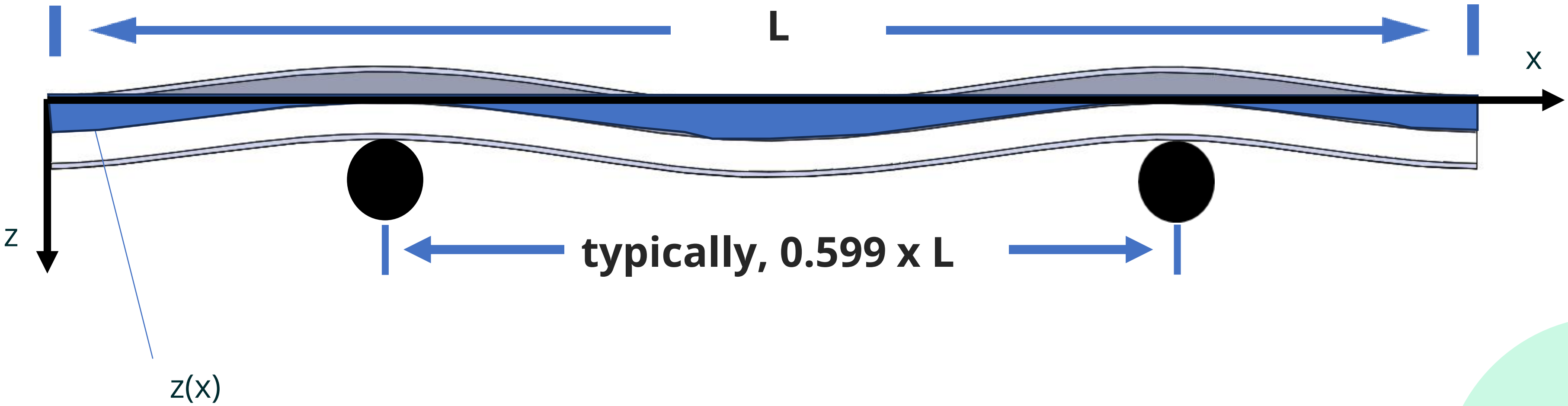


The deflection z(x) is a function of the stiffness, weight, cross section of the beam and the location of the supports

Basic Measurement Principles

Artifact based reference length-fixturing line standards

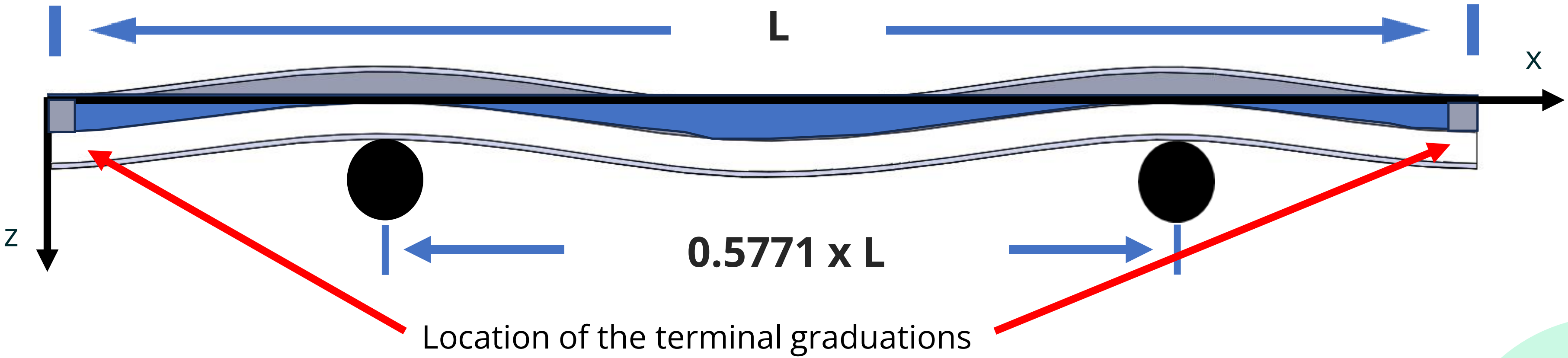
Calculate location of the supports by minimize the area of the curve below the x-axis and between the terminal graduations of the reference length



Basic Measurement Principles

Artifact based reference length-fixturing line standards

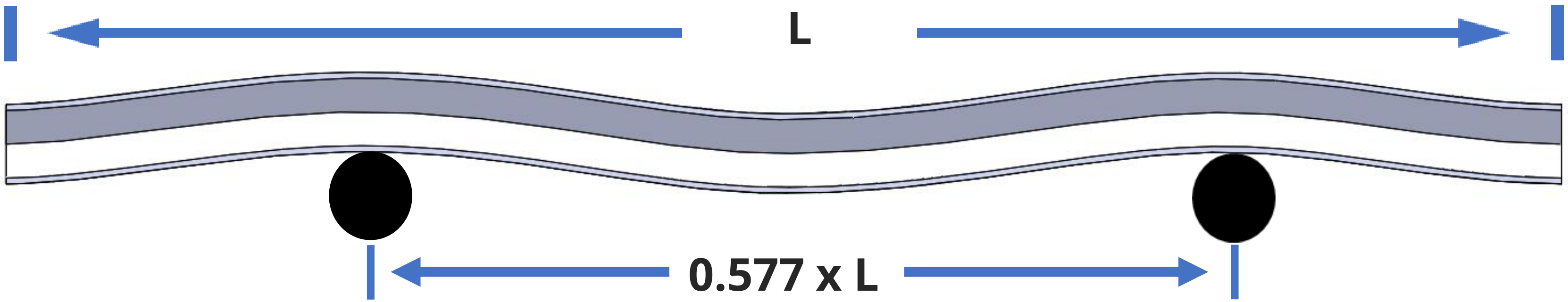
In this image the lines are no longer at the end but displace slightly. We calculate the location of the supports that minimize the blue area. Fort the prototype meter bar, this value is 0.5771 times the overall length of the artifact.



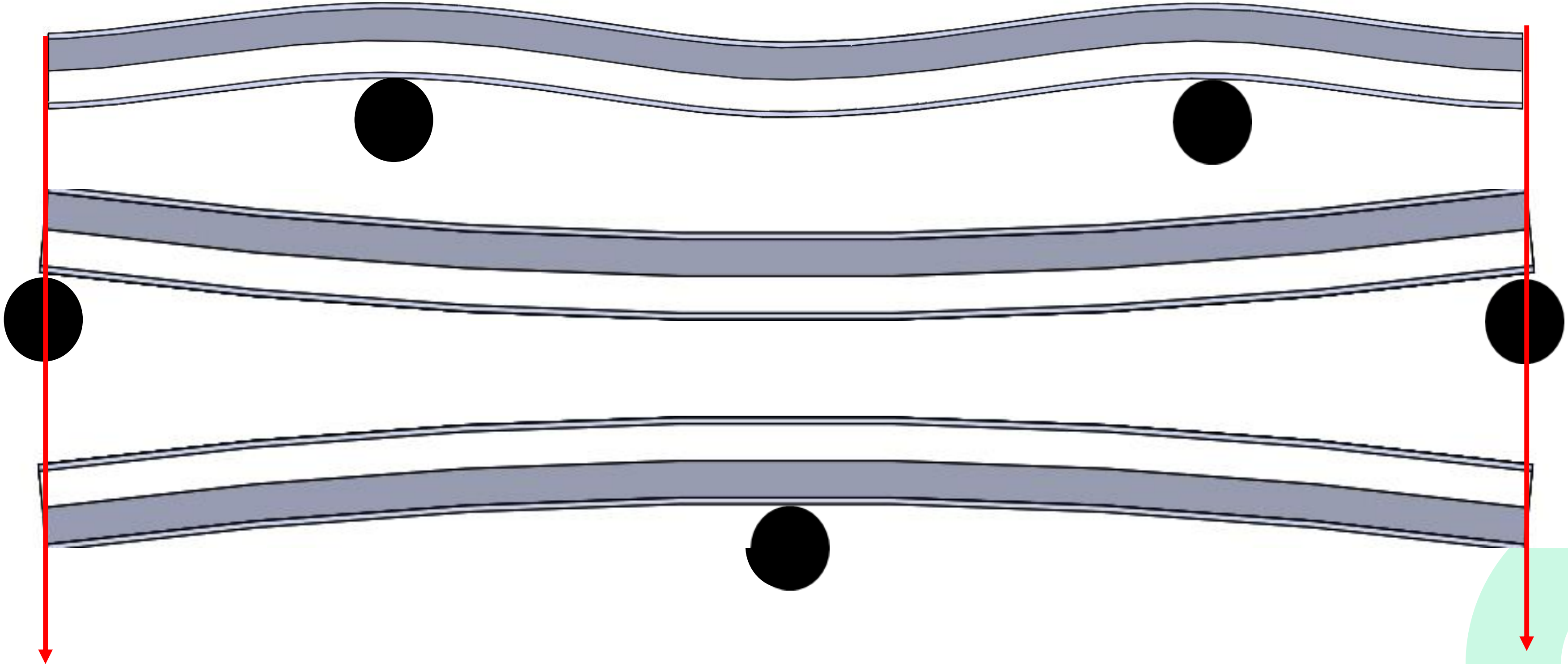
Basic Measurement Principles

Artifact based reference length-fixturing end standards

End standards are supported on the Airy points. These are the points in which properly manufactured end standards have vertical ends faces when supported horizontally and vertically.

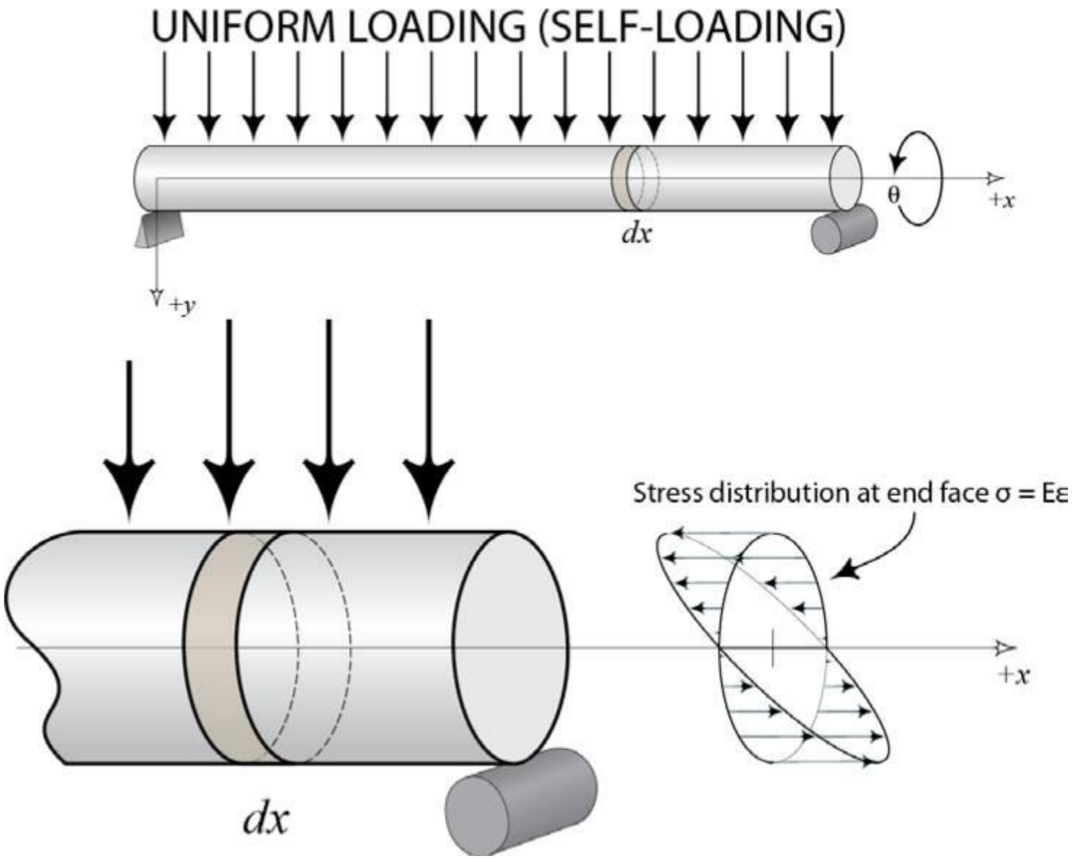


End standards are supported on the Airy points.



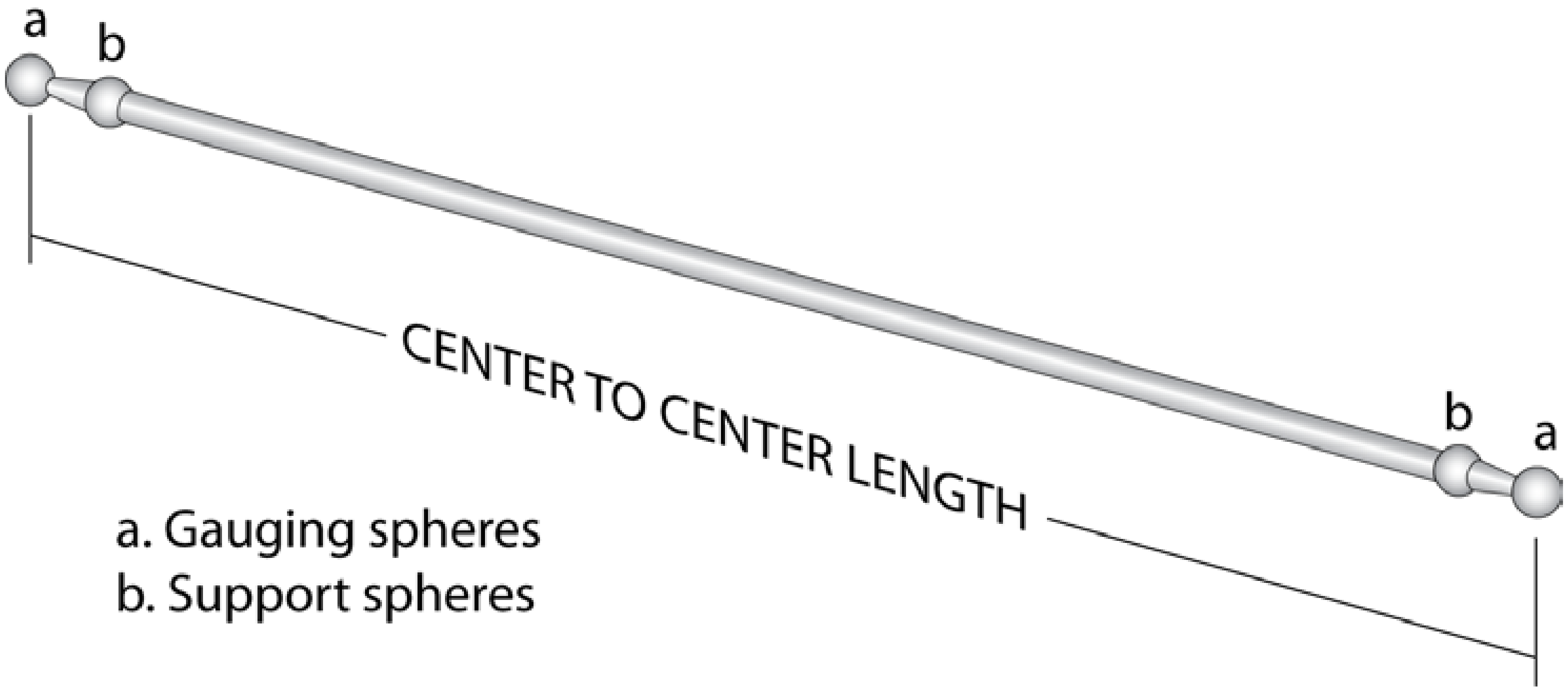
Basic Measurement Principles

Artifact based reference length-fixturing end standards



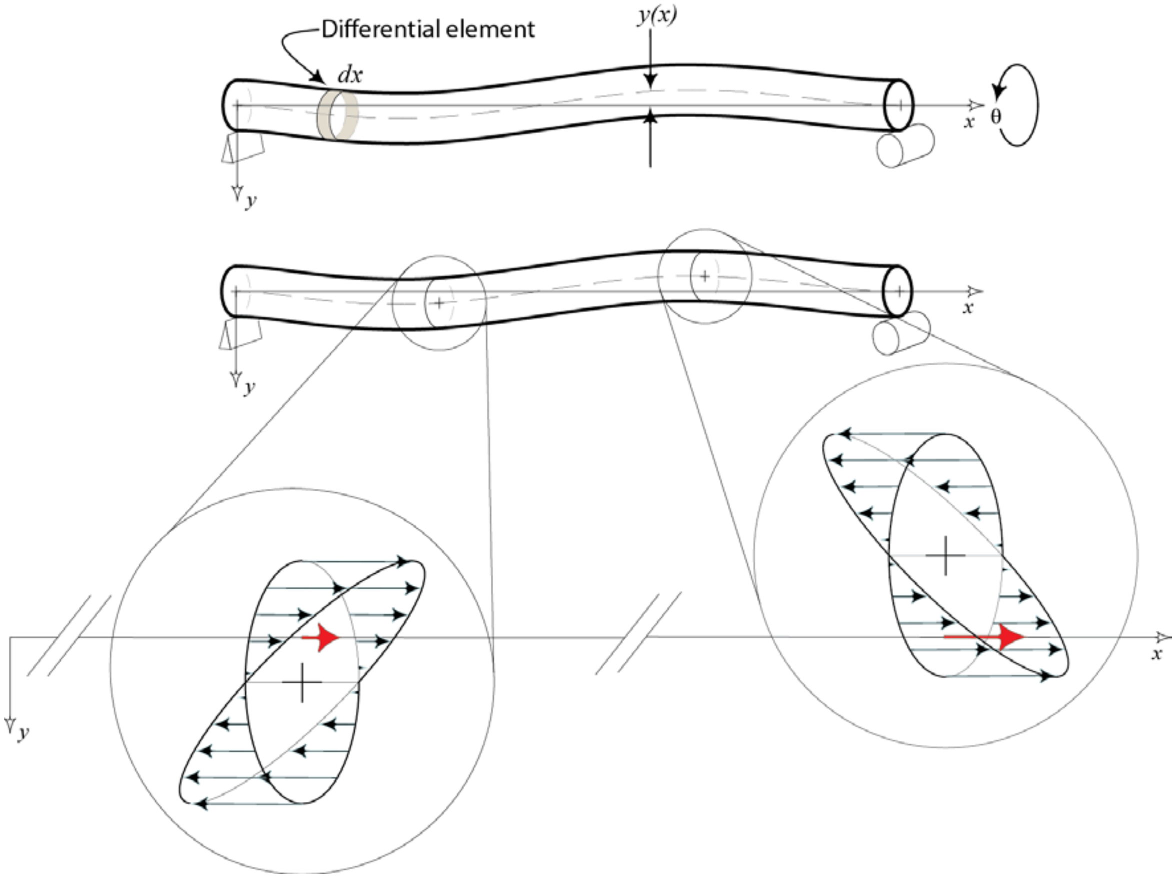
Basic Measurement Principles

Artifact based reference length-fixturing end standards



Basic Measurement Principles

Artifact based reference length-fixturing end standards



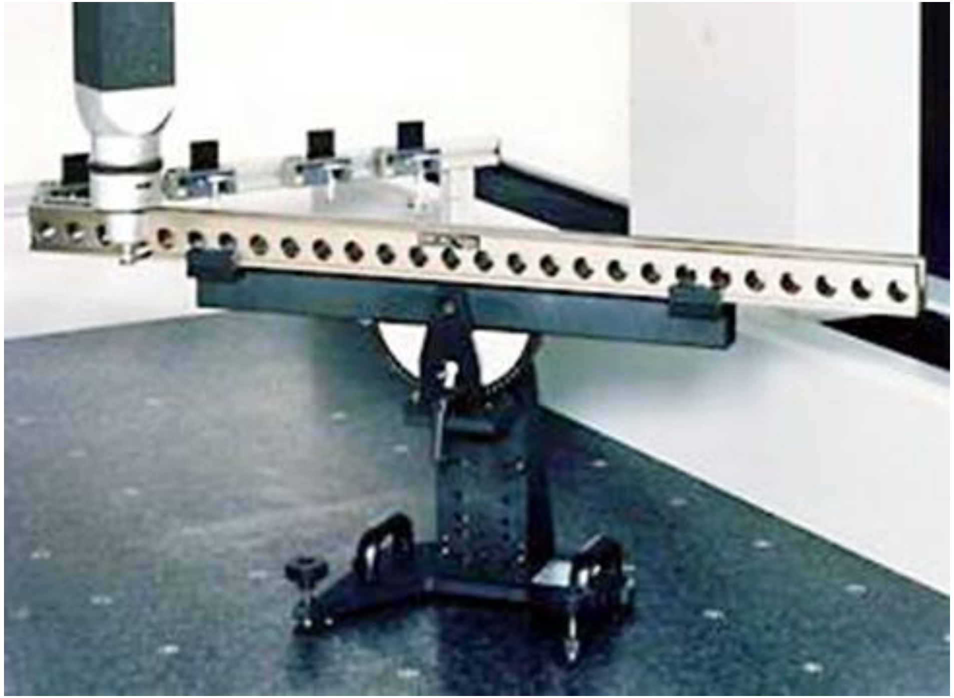
Basic Measurement Principles

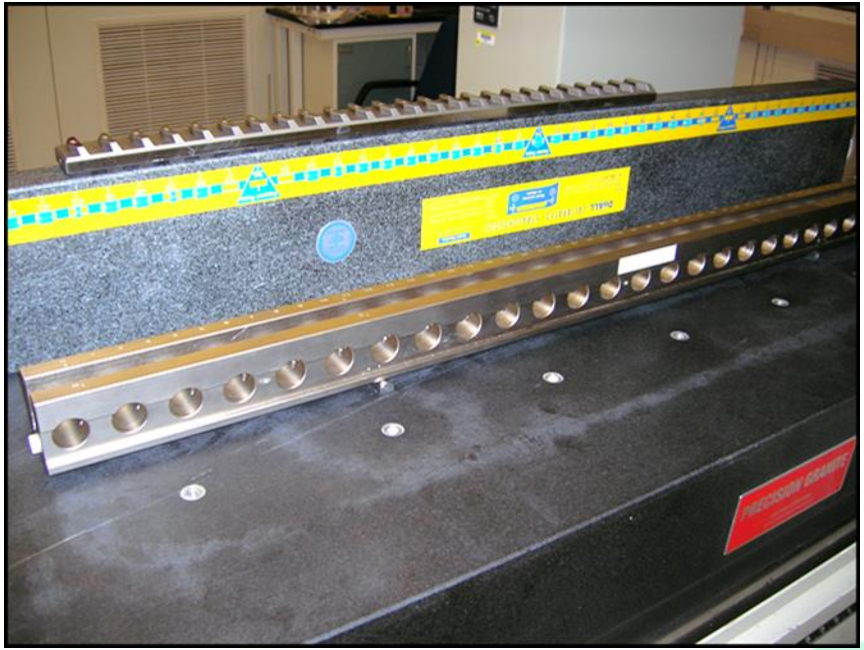
Artifact based reference length-transfer of technology

Certain equipment, instruments, software, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement of any product or service by NIST, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

Basic Measurement Principles

Measurement principles for reference artifacts





Basic Measurement Principles

Optically based reference length -displacement interferometry

Laser interferometry is among the most commonly used methods, in NMIs, to establish reference lengths for dissemination of traceable measurements.

For long length measurements time of flight techniques are employed. (will not cover here)

For lengths 80 meters or less, in a laboratory, displacement interferometry is typically used.

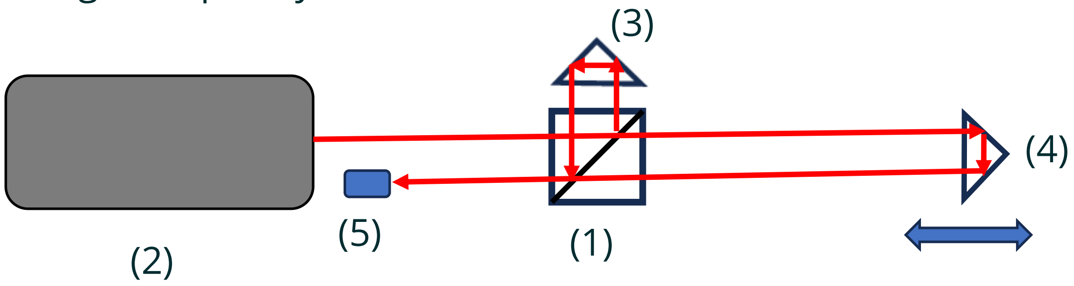
There are many different types of displacement interferometers. We will describe the most commonly used systems.

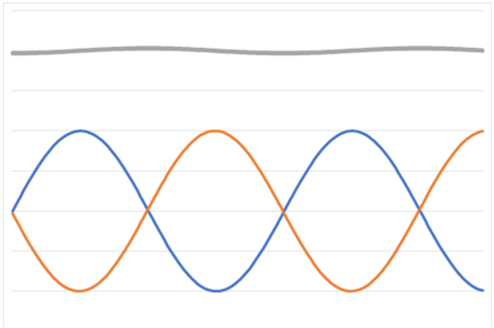
Basic Measurement Principles

Optically based reference length - displacement interferometry (homodyne)

Generic displacement interferometer coherent laser light source (laser)

Single frequency laser





phase of measurement beam changes relative to reference beam.

Photodetector measures intensity of the combined beams. Change from light to dark fringe represents ½ the wavelength of light, which is 2 times the actual displacement of the measurement retro-reflector

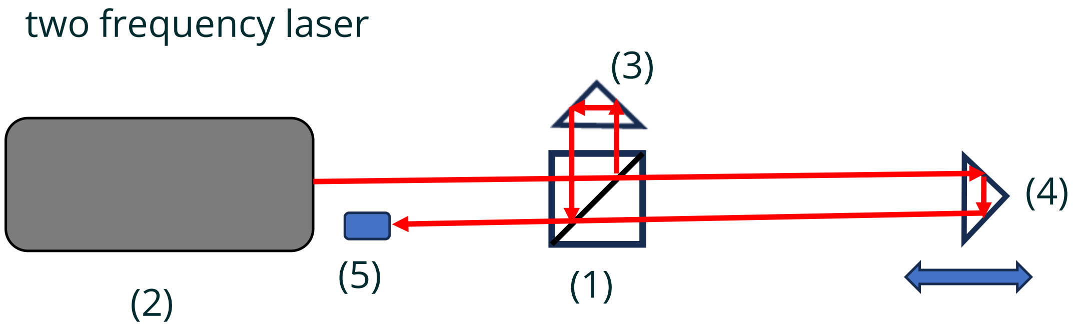
(1) Polarizing beam splitting interferometer
(2) Laser head
(3) Reference retro-reflector
(4) Measurement retro-reflector
(5) Signal processing electronics

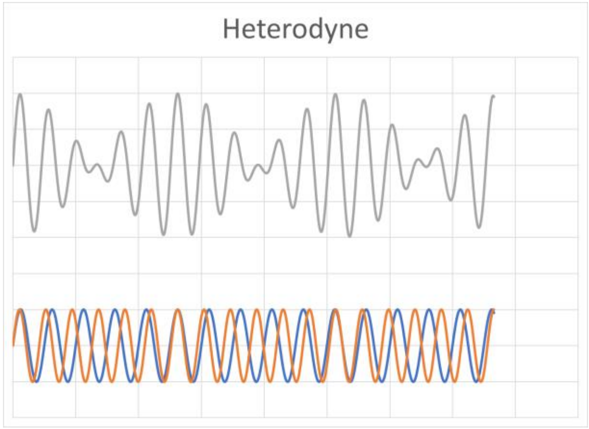
https://iopscience.iop.org/article/10.1088/1681-7575/ac1456/pdf

Basic Measurement Principles

displacement interferometry (heterodyne)

Generic displacement interferometer coherent laser light source (laser)





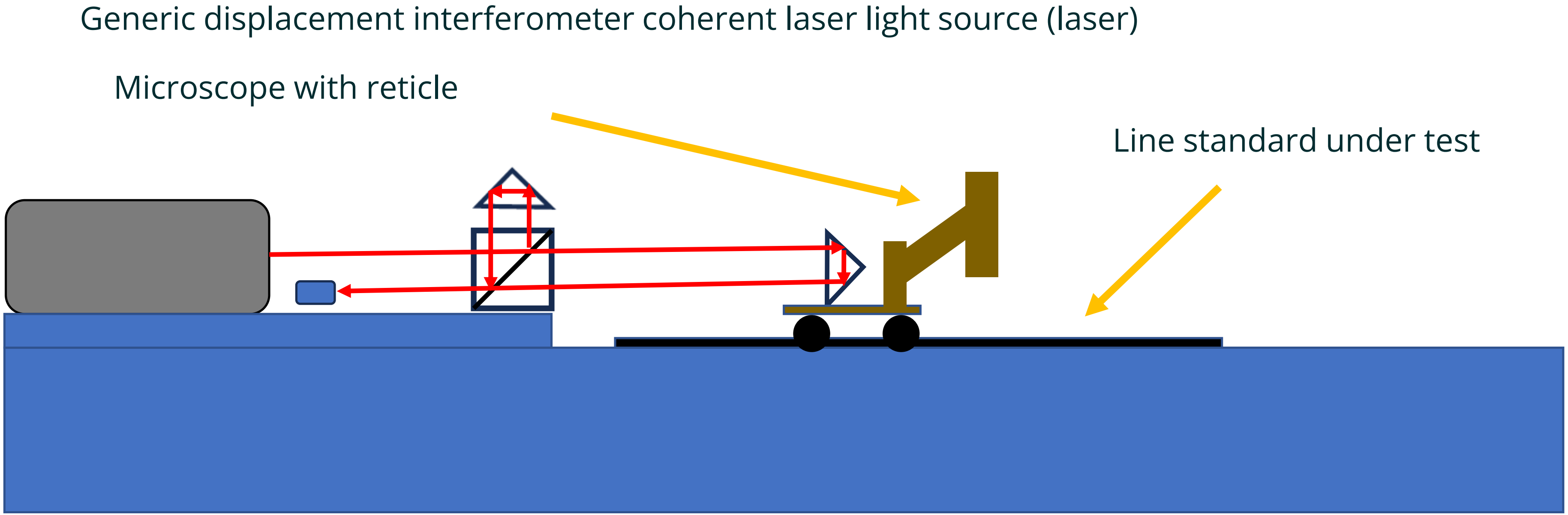
(1) Polarizing beam splitting interferometer
(2) Laser head, two frequencies
(3) Reference retro-reflector
(4) Measurement retro-reflector
(5) Signal processing electronics

The frequency of the measurement beam shifts up or down , due to the doppler effect, depending on the direction of motion of the measurement retro-reflector

https://iopscience.iop.org/article/10.1088/1681-7575/ac1456/pdf

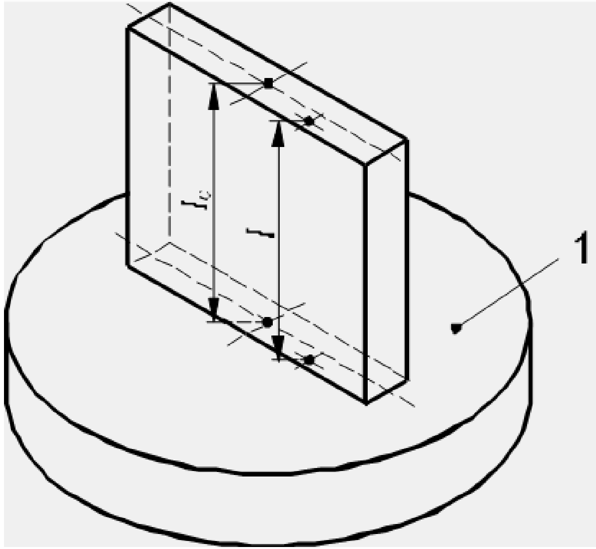
Basic Measurement Principles

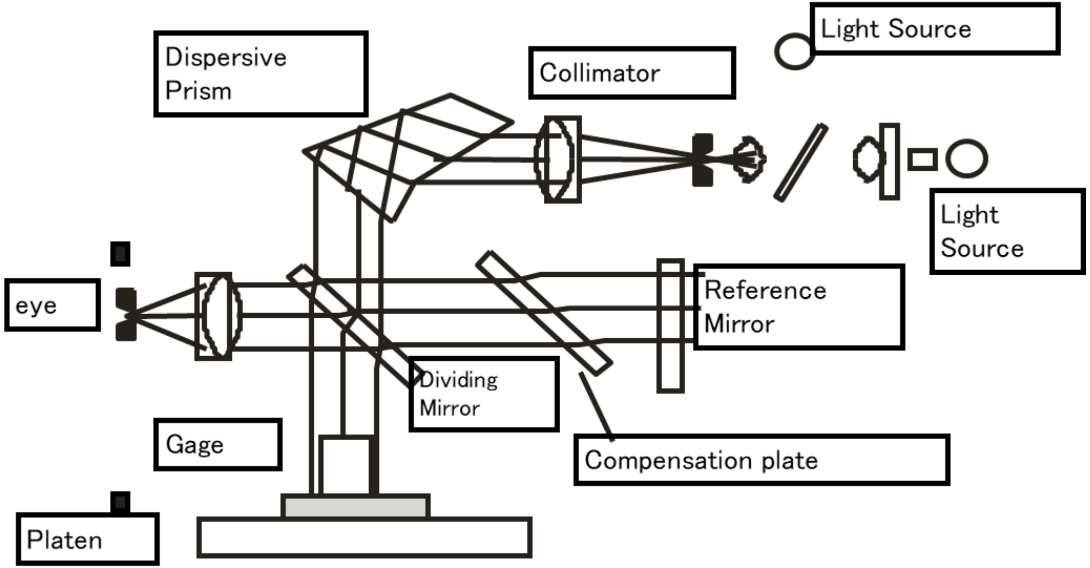
displacement interferometry for line standards



Basic Measurement Principles

Displacement interferometer - Koesters





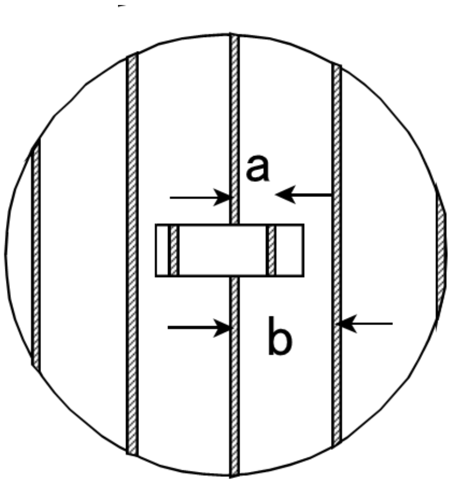
gauge block, *l*
by convention, the perpendicular distance between any particular point of the measuring face and the plane surface of an auxiliary plate of the same material and surface texture upon which the other measuring face has been wrung

With lasers the compensation plate and dispersive prism are not needed.

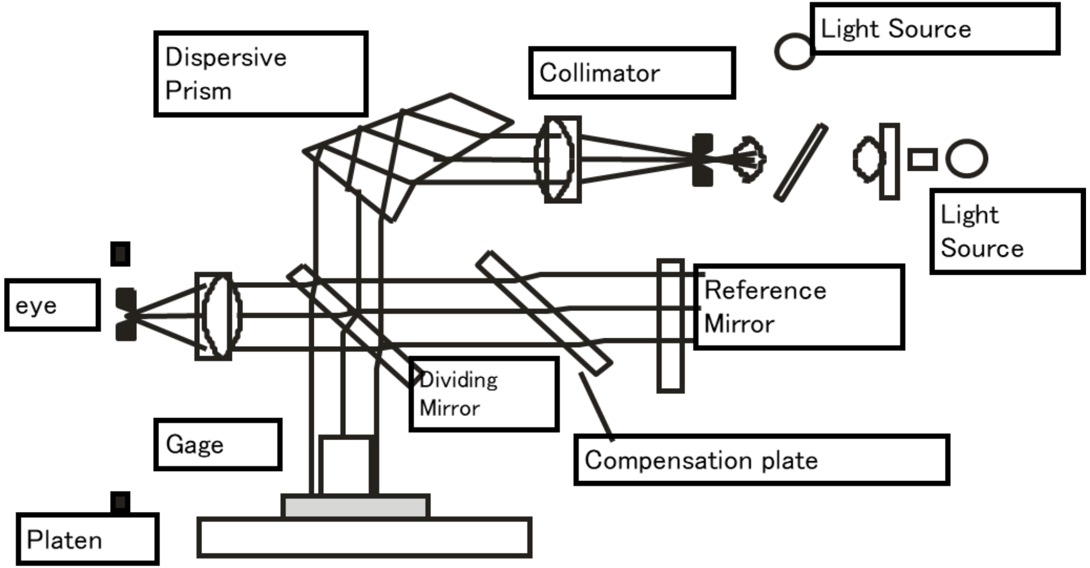
The entrance slit and viewing slit are in line, thus there is no obliquity correction.

Basic Measurement Principles

Displacement interferometer - Koesters



Fringe Fraction = a/b



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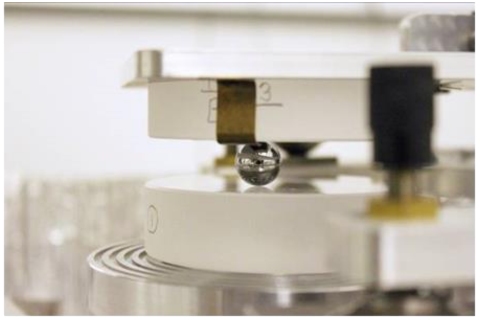
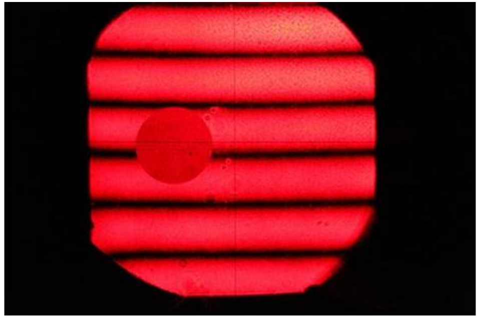
Basic Measurement Principles

NIST Strang Viewer Sphere Interferometer



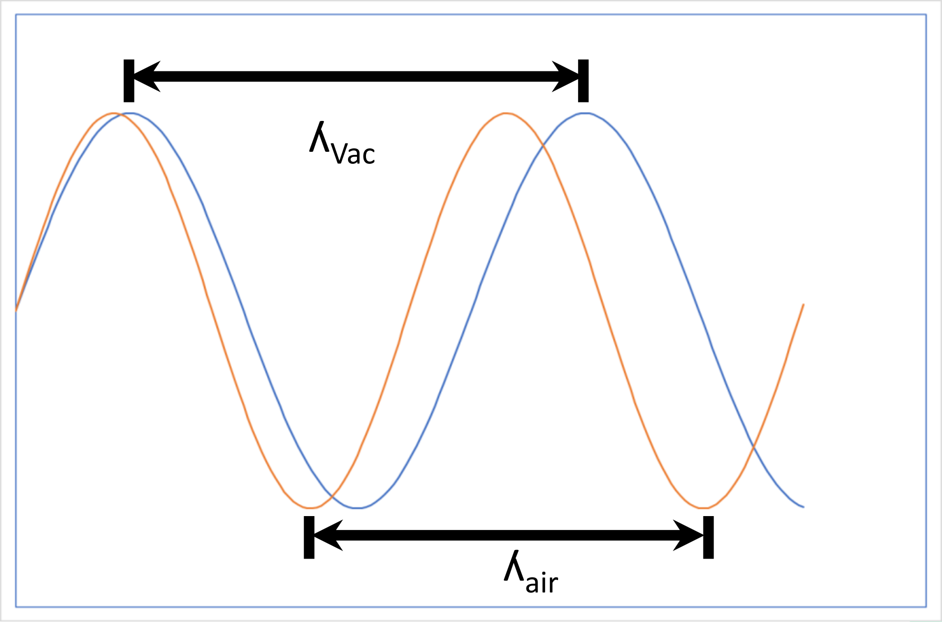


The ball is used as a spacer between two optical flats. When illuminated with monochromatic light we see fringes. The center of the ball with respect to the fringes gives a fringe fraction. Repeated with other color light will give enough information to determine the ball diameter with an uncertainty well under 25 nm.

Basic Measurement Principles

Optical interferometry

Optical interferometry relies on the wavelength of light as the scale for measurement.



The wavelength in air depends on the temperature, pressure, humidity and the content of the air.

The vacuum wavelength λ_{Vac}, must be corrected for the index of refraction of air to determine the wavelength in air, λ_{air}.

$\lambda_{air} = \lambda_{Vac} / n$ (where n is the refractive index of air).

Basic Measurement Principles

Optical interferometry

NIST a webpage called the engineering metrology webpage that provide information on making this correction. https://emtoolbox.nist.gov/Wavelength/Documentation.asps

Webpage provides a tool to investigate two equations for correction the wavelength of light in air using the Ciddor and Edl’en equations.

The applicability of these equations and relevant assumptions and principles of measurement are discussed.

The refractive index is the phase index only. If the group index is desired, another source is required.

Basic Measurement Principles

Other secondary realizations of the meter

Silicon lattice parameter and X-ray interferometry for nanometer and sub-nanometer scale applications in dimensional nanometrology. (picometer resolution is possible)

Silicon lattice and transmission electron Microscopy for dimensional nanometrology.

Height of monoatomic steps of crystalline silicon surfaces.

https://iopscience.iop.org/article/10.1088/1681-7575/ac1456/pdf

Measurands

Measurands

Definition from the JCGM 200:2012

2.3 (2.6)
measurand
quantity intended to be measured

NOTE 1 The specification of a measurand requires knowledge of the kind of quantity, description of the state of the phenomenon, body, or substance carrying the quantity, including any relevant component, and the chemical entities involved.

NOTE 2 In the second edition of the VIM and in IEC 60050-300:2001, the measurand is defined as the 'quantity subject to measurement'.

NOTE 3 The measurement, including the measuring system and the conditions under which the measurement is carried out, might change the phenomenon, body, or substance such that the quantity being measured may differ from the measurand as defined. In this case, adequate correction is necessary.

Measurands

Definition from the JCGM 200:2012

2.3 (2.6)
measurand
quantity intended to be measured
....

- EXAMPLE 1 The potential difference between the terminals of a battery may decrease when using a voltmeter with a significant internal conductance to perform the measurement. The open-circuit potential difference can be calculated from the internal resistances of the battery and the voltmeter.

- EXAMPLE 2 The length of a steel rod in equilibrium with the ambient Celsius temperature of 23 °C will be different from the length at the specified temperature of 20 °C, which is the measurand. In this case, a correction is necessary.

NOTE 4 In chemistry, “analyte”, or the name of a substance or compound, are terms sometimes used for ‘measurand’. This usage is erroneous because these terms do not refer to quantities.

Measurands

CCL Length Services Classification DimVIM

CLASS

Consultative Committee for Length (CCL)
Working Group on the MRA (WG-MRA)

CCL Length Services Classification (DimVIM)

DimVIM : Multilingual CMC classification scheme

CCL Service Category	Instrument or Artifact	Measurand(s)
	English Language Approved Terms	
1 Radiations of the Mise en Pratique		
1.1 Laser Radiations		
1.1.1	frequency stabilized laser	vacuum wavelength; optical frequency
1.2 Lamp Radiations		
1.2.1	spectral lamp	vacuum wavelength
2 Linear Dimensions		
2.1 Length Instruments		
2.1.1	(laser, length) interferometer (system, optics, refractometer)	error of indicated displacement; wavelength compensation
2.1.2	EDM instrument	error of indicated distance
2.1.3	1-D measuring machine	error of indicated [size; displacement]
2.1.4	height measuring instrument	error of indicated [vertical size; displacement]
2.1.5	1-D displacement [transduscer, actuator] (LVDT, PZT,…)	error of indicated displacement
2.1.6	gauge block comparators	error of indicated displacement
2.1.7	dial-indicator tester	error of indicated displacement
2.2 End Standards		
2.2.1	gauge block	central length; variation in length; thermal expansivity; length difference of gauge block pairs
2.2.2	length bar (long gauge block)	central length; variation in length; thermal expansivity
2.2.3	[plane, thread] micrometer setting rod	length
2.2.4	step gauge	face spacing
2.2.5	gap gauge	face spacing
2.2.6	feeler (thickness) gauge	thickness
2.3 Line Standards		
2.3.1	precision line scale	line spacing
2.3.2	stage micrometer	line spacing
2.3.3	grid plate	grid point coordinates
2.3.4	1-D grating	pitch
2.3.5	2-D grating	pitch; orthogonality
2.3.6	linewidth standard	linewidth, spacewidth, pitch
2.3.7	(surveyor, engineer, pi) tape, (geodetic) wire	line spacing
2.3.8	surveyor leveling rod	line spacing
2.3.9	engineer or machinist scale, steel	line spacing
2.4 Diameter Standards		
2.4.1	external cylinder (plug, piston, pin, wire)	diameter
2.4.2	internal cylinder (ring)	diameter
2.4.3	sphere (ball)	diameter
2.5 Standards of 1D Dimensions		
2.5.1	standard of 1D point-to-point dimensions	sizes, distances

Measurands

CCL Length Services Classification DimVIM

CCL Service Category	Instrument or Artifact	Measurand(s)
	English Language Approved Terms	
3 Angle		
3.1 Angle by Circle Dividers		
3.1.1	optical polygon	face angle; pyramid error; face flatness
3.1.2	index table	index angle
3.1.3	rotary table, rotary encoder scale	position angle
3.2 Small-Angle Generators		
3.2.1	sine (bar, table)	cylinder spacing; angle
3.3 Angle Instruments		
3.3.1	autocollimator	error of indicated angle; axes orthogonality
3.3.2	electronic level	error of indicated inclination angle
3.3.3	clinometer	error of indicated inclination angle
3.3.4	spirit (bubble) level	error of indicated inclination angle
3.3.5	theodolite	error of indicated angle; axes orthogonality
3.3.6	(bevel) protractor	error of indicated angle
3.3.7	squareness tester	error of indicated [squareness; straightness]
3.4 Angle Artifacts		
3.4.1	angle block	included angle; pyramid error; face flatness
3.4.2	90° (steel, granite, try) square	squareness
3.4.3	90° cylinder square	squareness
3.4.4	cone (taper) gauge	cone angle; diameter
3.5 Angle Prisms		
3.5.1	optical square (pentaprism)	deviation angle
3.5.2	retroreflection (cube-corner, cat-eye) prism	deviation angle
4 Form		
4.1 Flatness Standards		
4.1.1	optical flat	flatness
4.1.2	optical (parallel, wedge)	parallelism; wedge angle
4.1.3	surface plate	flatness
4.2 Roundness Standards		
4.2.1	external cylinder	roundness
4.2.2	internal cylinder	roundness
4.2.3	sphere (hemisphere)	roundness
4.2.4	magnification standard (eg flick standard)	roundness; amplitude & phase harmonic content
4.3 Straightness Standards		
4.3.1	straight edge	straightness
4.3.2	cylindrical straightness standard	straightness
4.3.3	straightness of guideway	straightness
4.4 Cylindricity Standards		
4.4.1	external cylinder	cylindricity
4.4.2	internal cylinder	cylindricity
4.5 Optical Standards		
4.5.1	lens, radius standards	focal length, radius of curvature

Measurands

CCL Length Services Classification DimVIM

CCL Service Category	English Language Approved Terms: Instrument or Artifact	English Language Approved Terms: Measurand(s)
5 Complex Geometry		
5.1 Surface Texture Standards		
5.1.1	(groove) depth (step height) standard (eg ISO 5436-1 Type A)	step height; (groove) depth
5.1.2	tip-condition standard (eg ISO 5436-1 Type B)	radii, angle
5.1.3	spacing standard (eg ISO 5436-1 Type C)	[amplitude; wavelength] parameters
5.1.4	roughness standard (eg ISO 5436-1 Type D)	ISO roughness parameters
5.1.5	profile coordinate standard (eg ISO 5436-1 Type E)	profile coordinates
5.1.6	softgauge (reference software data set, eg ISO 5436-2 Type F1)	error in calculated [dimensions; parameters]
5.2 Screw Standards		
5.2.1	thread plug, plain	[simple] pitch diameter; pitch; flank angle
5.2.2	thread plug, tapered	[simple] pitch diameter; pitch; flank angle; taper angle
5.2.3	thread ring, plain	[simple] pitch diameter; pitch; flank angle
5.2.4	thread ring, tapered	[simple] pitch diameter; pitch; flank angle; taper angle
5.2.5	internal API screw thread gauge	API thread parameters
5.2.6	external API screw thread gauge	API thread parameters
5.3 Gear Standards		
5.3.1	Involute gear	profile slope [form, total] deviation, helix slope [form, total] deviation, single [cumulative] pitch deviation
5.3.2	bevel gear	pitch; involute; bevel angle
5.3.3	gear pitch master	total cumulative pitch deviation
5.3.4	gear lead master	[total cumulative, single] pitch deviation
5.3.5	gear involute master	involute profile [slope, form] deviation
5.4 CMM Artifacts		
5.4.1	ball (hole, bore) plate	[ball; hole] center coordinates
5.4.2	ball bar	ball spacing
5.4.3	large CMM artifact	interval distances
5.4.4	reference software	error in calculated [dimensions; parameters; features]
5.4.5	test circle for imaging probing systems	diameter; roundness
5.5 2-D, 3-D Instruments		
5.5.1	measuring projector	error of indicated [size; location; shape]
5.5.2	measuring microscope	error of indicated [size; location; shape]
5.5.3	CMM	error of indicated [size; location; shape]
5.5.4	laser tracking measuring system	error of indicated [size; location; shape]
5.5.5	motion (translation, angle) stage	error in prescribed [translation; angular] motion
5.5.6	profile instruments	error of indicated [form, shape, size, surface texture parameters]
5.5.7	(flatness, wavefront) interferometer	error of indicated [flatness; wavefront] deviation
5.5.8	form-measuring machine	error of indicated form [roundness, straightness,] deviation
5.6 Hardness		
5.6.1	hardness indenter [Rockwell, Vickers]	tip [size, shape]

Measurands

CCL Length Services Classification DimVIM

CCL Service Category	English Language Approved Terms	
	Instrument or Artifact	Measurand(s)
6 Various Dimensional		
6.1 Hand Instruments		
6.1.1	external micrometer	error of indicated size
6.1.2	micrometer head	error of indicated displacement
6.1.3	depth micrometer	error of indicated depth
6.1.4	caliper	error of indicated size
6.1.5	depth gauge	error of indicated depth
6.1.6	internal two-point (bore) micrometer	error of indicated diameter
6.1.7	internal three-point (bore) micrometer	error of indicated diameter
6.1.8	dial gauge	error of indicated displacement
6.1.9	snap gauge (internal, external)	error of indicated size
6.2 Pressure Artifacts		
6.2.1	piston/cylinder assembly	3-D size, shape
6.3 Thermal Expansivity		
6.3.1	thermal expansion artifact	thermal expansion coefficient
6.4 Long Distance		
6.4.1	geodetic baseline	interval distances
6.5 Reference Materials		
6.5.1	standard particle	particle size; shape
6.5.2	[sieve, mesh] opening	aperture [size, shape]
6.6 Layer thickness		
6.6.1	layer thickness standard	layer thickness

Measurands

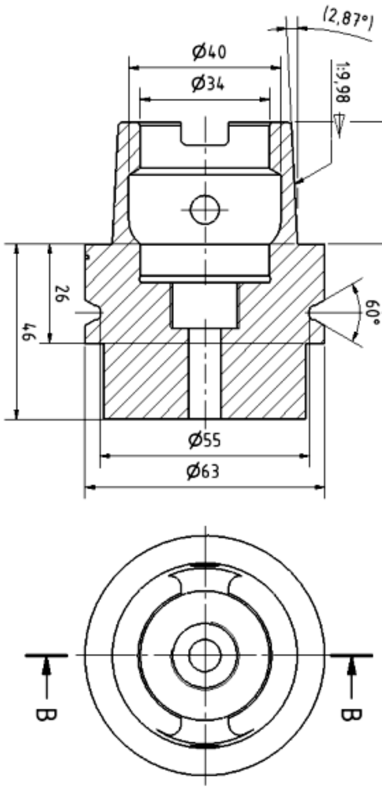
It's complicated

What is of most interest is how do our manufacturers determine the uncertainty in measurements of real parts?

This is a question the CCL has been thinking about CMMs are very flexible and there are methods that do a reasonable job at understand how to help the manufacturer's resolve this problem.

Much of this has to do with discreet sampling, which is not typically the best way to ensure fit and function.

Virtual CMM is employed by some NMI's to provide special measurements for critical scientific research projects.



Measurands

The future

2 Background

CMCs specific to an instrument or standard type are unable to capture situations where possibly different standards can be calibrated in similar conditions, with similar measuring systems and with similar calibration uncertainty. As long as the measurand and the equipment stay the same, calibrations of even diverse standards may be encompassed by a same flexible capability.

For this reason, a new entry is introduced in the DimVIM (rev. 10, see Annex B) to accommodate artefacts of diverse nature and shape in a single CMC, all sharing the same prominent feature, which is in fact the measurand under calibration.

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1.2.1	spectral lamp	vacuum wavelength
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2.1.2	EDM instrument	error of indicated distance
2.1.3	1-D measuring machine	error of indicated [size; displacement]
2.1.4	height measuring instrument	error of indicated [vertical size; displacement]
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2.2.2	length bar (long gauge block)	central length; variation in length; thermal expansivity
2.2.3	[plane, thread] micrometer setting rod	length
2.2.4	step gauge	face spacing
2.2.5	gap gauge	face spacing
2.2.6	feeler (thickness) gauge	thickness
2.3 Line Standards		
2.3.1	precision line scale	line spacing
2.3.2	stage micrometer	line spacing
2.3.3	grid plate	grid point coordinates
2.3.4	1-D grating	pitch
2.3.5	2-D grating	pitch; orthogonality
2.3.6	linewidth standard	linewidth, spacewidth, pitch
2.3.7	(surveyor, engineer, pi) tape, (geodetic) wire	line spacing
2.3.8	surveyor leveling rod	line spacing
2.3.9	engineer or machinist scale, steel	line spacing
2.4 Diameter Standards		
2.4.1	external cylinder (plug, piston, pin, wire)	diameter
2.4.2	internal cylinder (ring)	diameter
2.4.3	sphere (ball)	diameter
2.5 Standards of 1D Dimensions		
2.5.1	standard of 1D point-to-point dimensions	sizes, distances

Measurands

The future

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1.2 Lamp Radiations		
1.2.1	spectral lamp	vacuum wavelength

wavelength compensation

nent]

isplacement]

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2.2.2	length bar (long gauge block)	central length; variation in length; thermal expansivity
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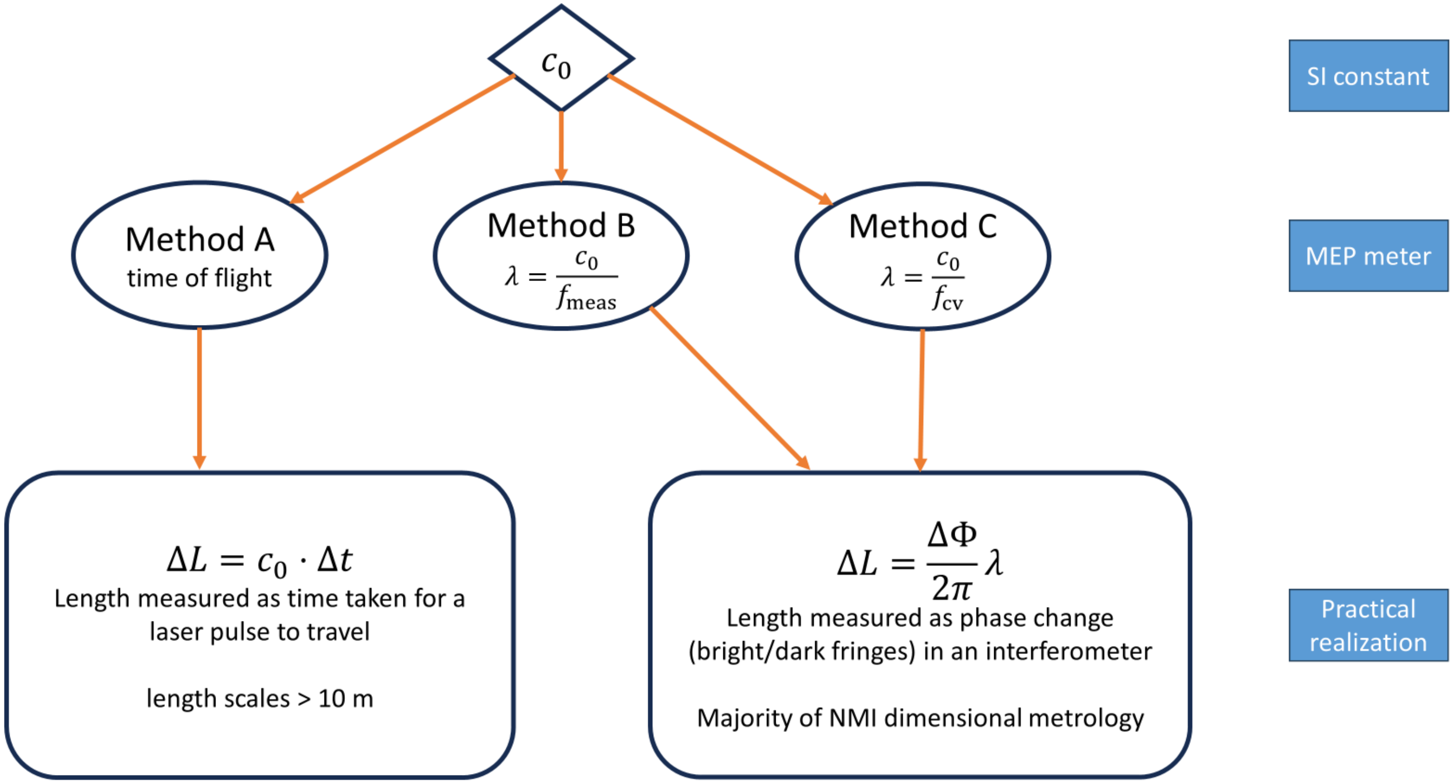
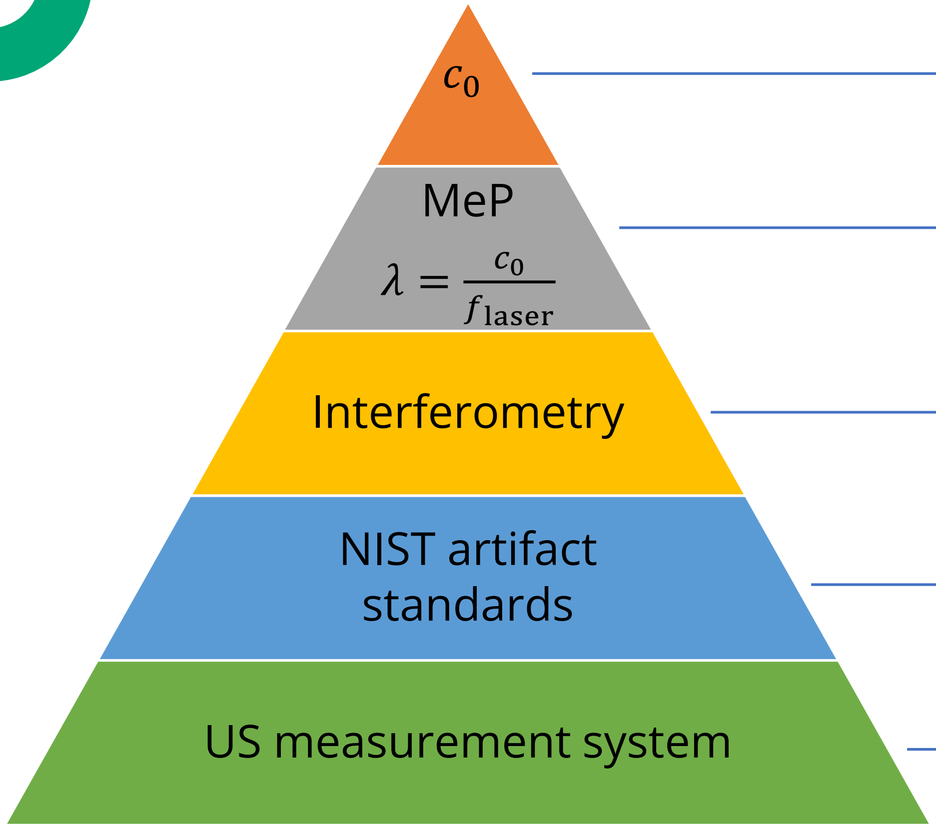
Traceability

Traceability



Traceability



The meter is defined by the speed of light

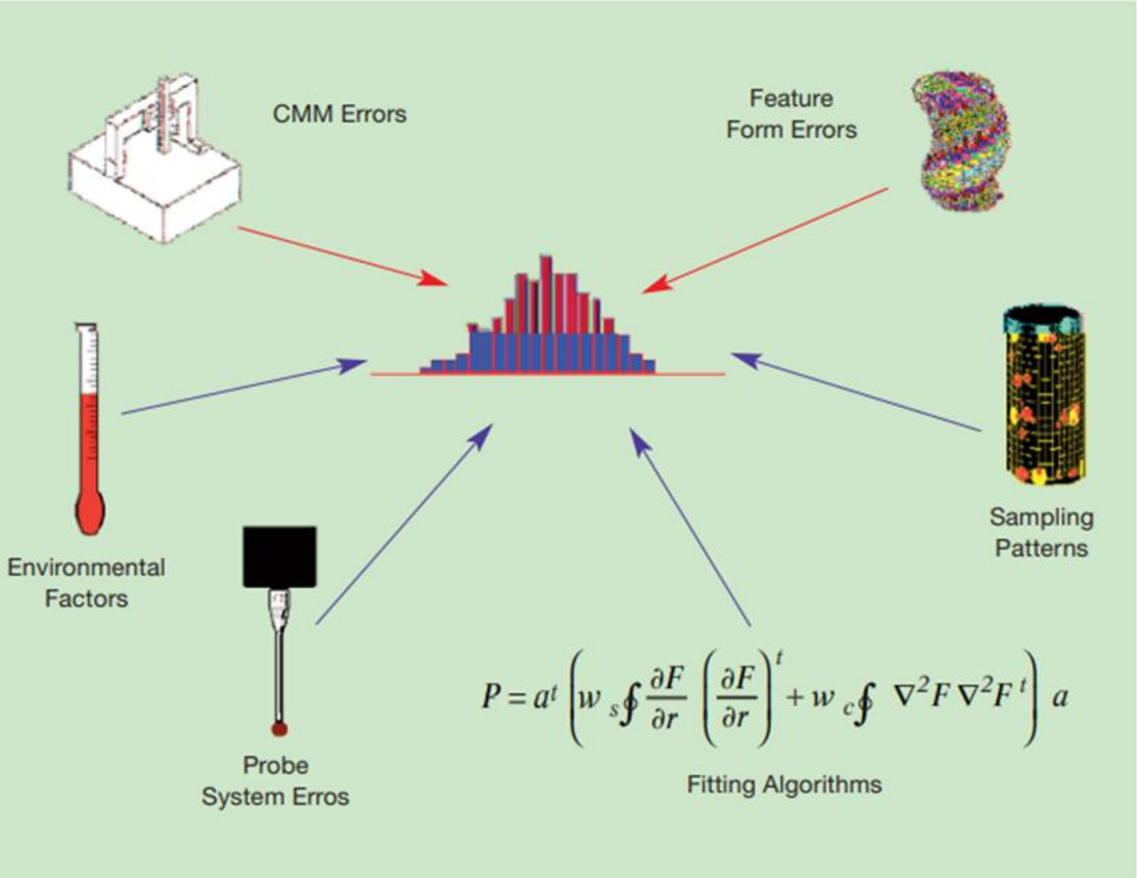
The speed of light is accessed via laser wavelength λ. The frequency of the laser f_{laser} is known/measured traceable to the SI second.

The laser of known wavelength feeds an interferometer. An interferometer functions like a ruler, whose spacings are exact multiples of $\lambda/2$

Interferometers are used to establish dimensions of precision artifacts traceable to the SI meter: diameter of spheres and cylinders, height of gage blocks, etc

Dissemination of the SI meter to industry is predominantly via artifacts calibrated by interferometry or by comparison to NIST artifact standards.

Traceability

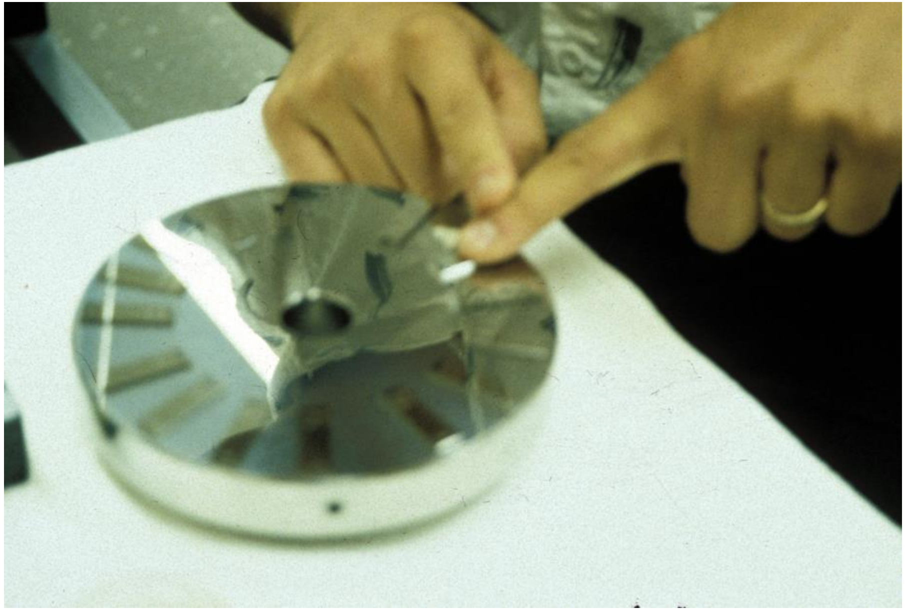


Dissemination

Dissemination

Calibrations services

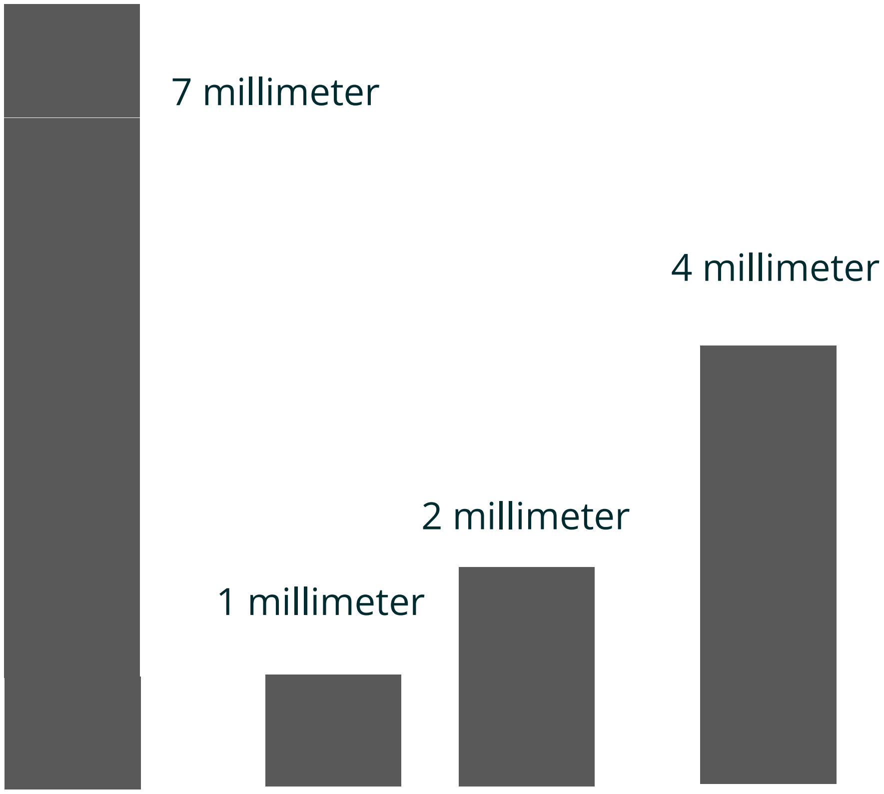
Standard gages approximately 3000-4000 gage blocks and other measurements per year.



Dissemination

Calibrations services

Wringing allows for significantly fewer calibrations

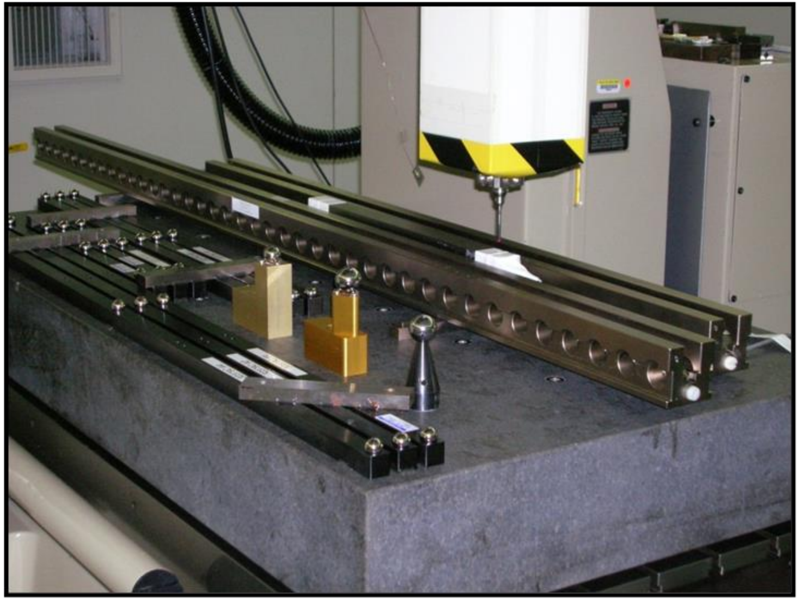


If reference lengths of 1, 2, 3, 4, 5, 6, 7 millimeters is needed, only four blocks are required to produce the lengths with negligible error.

Dissemination

NIST Calibration Services

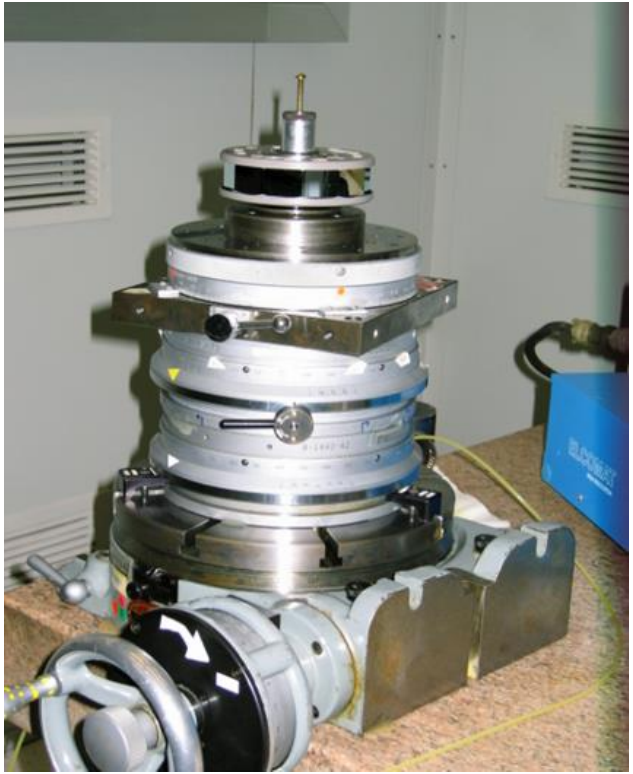
Calibration of customer reference gages, using coordinate measuring machines (CMM) Interferometric scales. Use reference artifacts, such as gauge blocks and reference spheres as reference masters.



Dissemination

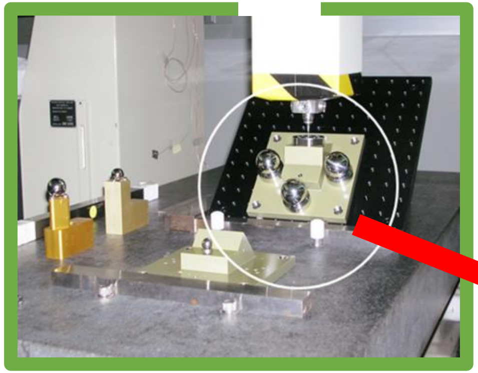
NIST Calibration Services

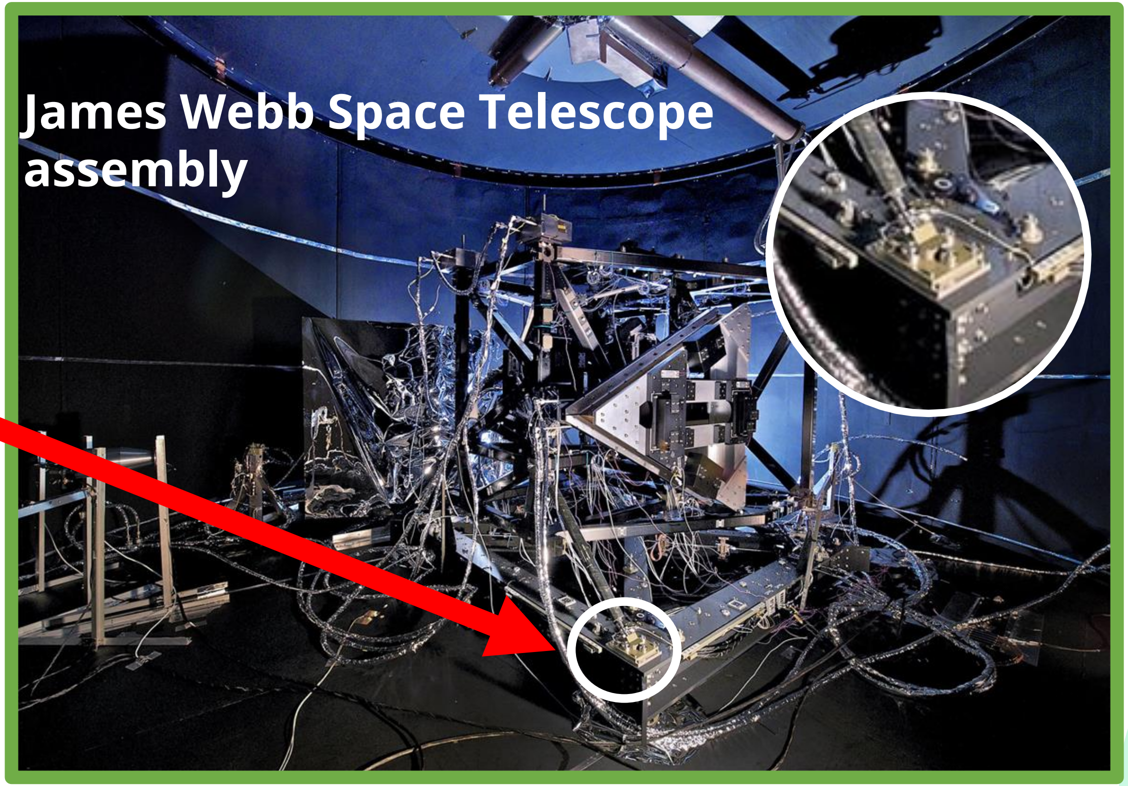
Index tables optical polygons and master spheres.



Dissemination

Perform high-value measurements for ground-breaking research efforts





Dissemination

Documentary standards

Not often thought of as dissemination of length

Output is instrument performance evaluation standards

Tests in the standard are designed to capture known error sources in the measuring technology

Develop error model for the measuring technologies. CMM have error compensation models that was developed by NIST

These error models along are used to develop a set of test that are sensitive to all the error sources in the instrument.

Test protocols are evaluated by users to help refine tests.

Procedures are then included in new or revised standards.

Structure of CCL and working Groups

Structure of the CCL and working groups

What is the function of the CCL

- Provides reviews and approvals of all length and angle-based international comparisons, with input from WGs, and DGs.
- Evaluates and communicates strategies to reduce the work required to establish equivalence among member labs for principal techniques.
- Monitors emerging needs of the international community for length based, high value, precision length measurements.
    1. New standards, documentary as well as physical
    2. Emerging technology

Structure of CCL and working groups

Working Groups

- **CCL-TG-DIG** — CCL TASK GROUP ON DIGITALIZATION
- **CCL-WG-MRA** — CCL WORKING GROUP ON THE CIPM MRA
- **CCL-WG-N** — CCL WORKING GROUP ON DIMENSIONAL NANOMETROLOGY
- **CCL-WG-S** — CCL WORKING GROUP ON STRATEGIC PLANNING
- **CCL-CCTF-WGFS** — CCL-CCTF FREQUENCY STANDARDS WORKING GROUP

Discussion Groups

- **CCL-DG1** — CCL DISCUSSION GROUP ON GAUGE BLOCKS
- **CCL-DG2** — CCL DISCUSSION GROUP ON THERMAL EXPANSION
- **CCL-DG3** — CCL DISCUSSION GROUP ON ANGLE
- **CCL-DG4** — CCL DISCUSSION GROUP ON CYLINDRICAL DIAMETER STANDARDS
- **CCL-DG5** — CCL DISCUSSION GROUP ON STEP GAUGES
- **CCL-DG6** — CCL DISCUSSION GROUP ON COORDINATE METROLOGY
- **CCL-DG7** — CCL DISCUSSION GROUP ON LINESCALES
- **CCL-DG8** — CCL DISCUSSION GROUP ON SURFACE TEXTURE
- **CCL-DG11** — CCL DISCUSSION GROUP ON MISE EN PRATIQUE LASERS AND FEMTOSECOND COMBS

https://www.bipm.org/en/committees/cc/ccl

Structure of the CCL and working groups

Primary activity of CCL members

- Inform BIPM of length-based issues and critical comparisons
- Review comparison…………….Review comparison……………..
- Produce draft of policy or process document
- Produce guidance documents and templates

Structure of the CCL and working groups

Challenges of CCL

- There are a large number of industrial measurements that are needed to ensure competence in principal techniques. (approximately 1626 CMCs listed)
- The range of principal techniques encompasses many different technologies. (interferometry, laser scanning, mechanical comparison techniques, 1 thru 3D coordinate metrology.) This activity could consume a lot of staff hours to address the needs of this community.
- Too many potential participants in CCL. Hierarchical comparisons are simply not feasible.

Structure of the CCL and working groups

DimVIM - service classification

Ver. 11 (Jul 2018) **English**

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3.1.2	index table	index angle
3.1.3	rotary table, rotary encoder scale	position angle
3.2 Small-Angle Generators		
3.2.1	sine (bar, table)	cylinder spacing; angle
3.3 Angle Instruments		
3.3.1	autocollimator	error of indicated angle; axes orthogonality
3.3.2	electronic level	error of indicated inclination angle
3.3.3	clinometer	error of indicated inclination angle
3.3.4	spirit (bubble) level	error of indicated inclination angle
3.3.5	theodolite	error of indicated angle; axes orthogonality
3.3.6	(bevel) protractor	error of indicated angle
3.3.7	squareness tester	error of indicated [squareness; straightness]
3.4 Angle Artifacts		
3.4.1	angle block	included angle; pyramid error; face flatness
3.4.2	90° (steel, granite, try) square	squareness
3.4.3	90° cylinder square	squareness
3.4.4	cone (taper) gauge	cone angle; diameter
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4 Form		
4.1 Flatness Standards		
4.1.1	optical flat	flatness
4.1.2	optical (parallel, wedge)	parallelism; wedge angle
4.1.3	surface plate	flatness
4.2 Roundness Standards		
4.2.1	external cylinder	roundness
4.2.2	internal cylinder	roundness
4.2.3	sphere (hemisphere)	roundness
4.2.4	magnification standard (eg flick standard)	roundness; amplitude & phase harmonic content
4.3 Straightness Standards		
4.3.1	straight edge	straightness
4.3.2	cylindrical straightness standard	straightness
4.3.3	straightness of guideway	straightness
4.4 Cylindricity Standards		
4.4.1	external cylinder	cylindricity
4.4.2	internal cylinder	cylindricity
4.5 Optical Standards		
4.5.1	lens, radius standards	focal length, radius of curvature

Ver. 11 (Jul 2018) **English**

CCL Service Category	English Language Approved Terms: Instrument or Artifact	Measurand(s)
5 Complex Geometry		
5.1 Surface Texture Standards		
5.1.1	(groove) depth (step height) standard (eg ISO 5436-1 Type A)	step height; (groove) depth
5.1.2	tip-condition standard (eg ISO 5436-1 Type B)	radii, angle
5.1.3	spacing standard (eg ISO 5436-1 Type C)	[amplitude; wavelength] parameters
5.1.4	roughness standard (eg ISO 5436-1 Type D)	ISO roughness parameters
5.1.5	profile coordinate standard (eg ISO 5436-1 Type E)	profile coordinates
5.1.6	softgauge (reference software data set, eg ISO 5436-2 Type F1)	error in calculated [dimensions; parameters]
5.2 Screw Standards		
5.2.1	thread plug, plain	[simple] pitch diameter; pitch; flank angle
5.2.2	thread plug, tapered	[simple] pitch diameter; pitch; flank angle; taper angle
5.2.3	thread ring, plain	[simple] pitch diameter; pitch; flank angle
5.2.4	thread ring, tapered	[simple] pitch diameter; pitch; flank angle; taper angle
5.2.5	internal API screw thread gauge	API thread parameters
5.2.6	external API screw thread gauge	API thread parameters
5.3 Gear Standards		
5.3.1	Involute gear	profile slope [form, total] deviation, helix slope [form, total] deviation, single [cumulative] pitch deviation
5.3.2	bevel gear	pitch; involute; bevel angle
5.3.3	gear pitch master	total cumulative pitch deviation
5.3.4	gear lead master	[total cumulative, single] pitch deviation
5.3.5	gear involute master	involute profile [slope, form] deviation
5.4 CMM Artifacts		
5.4.1	ball (hole, bore) plate	[ball; hole] center coordinates
5.4.2	ball bar	ball spacing
5.4.3	large CMM artifact	interval distances
5.4.4	reference software	error in calculated [dimensions; parameters; features]
5.4.5	test circle for imaging probing systems	diameter; roundness
5.5 2-D, 3-D Instruments		
5.5.1	measuring projector	error of indicated [size; location; shape]
5.5.2	measuring microscope	error of indicated [size; location; shape]
5.5.3	CMM	error of indicated [size; location; shape]
5.5.4	laser tracking measuring system	error of indicated [size; location; shape]
5.5.5	motion (translation, angle) stage	error in prescribed [translation; angular] motion
5.5.6	profile instruments	error of indicated [form, shape, size, surface texture parameters]
5.5.7	(flatness, wavefront) interferometer	error of indicated [flatness; wavefront] deviation
5.5.8	form-measuring machine	error of indicated form [roundness, straightness,] deviation
5.6 Hardness		
5.6.1	hardness indenter [Rockwell, Vickers]	tip [size, shape]

Ver. 11 (Jul 2018) **English**

CCL Service Category	English Language Approved Terms: Instrument or Artifact	Measurand(s)
6 Various Dimensional		
6.1 Hand Instruments		
6.1.1	external micrometer	error of indicated size
6.1.2	micrometer head	error of indicated displacement
6.1.3	depth micrometer	error of indicated depth
6.1.4	caliper	error of indicated size
6.1.5	depth gauge	error of indicated depth
6.1.6	internal two-point (bore) micrometer	error of indicated diameter
6.1.7	internal three-point (bore) micrometer	error of indicated diameter
6.1.8	dial gauge	error of indicated displacement
6.1.9	snap gauge (internal, external)	error of indicated size
6.2 Pressure Artifacts		
6.2.1	piston/cylinder assembly	3-D size, shape
6.3 Thermal Expansivity		
6.3.1	thermal expansion artifact	thermal expansion coefficient
6.4 Long Distance		
6.4.1	geodetic baseline	interval distances
6.5 Reference Materials		
6.5.1	standard particle	particle size; shape
6.5.2	[sieve, mesh] opening	aperture [size, shape]
6.6 Layer thickness		
6.6.1	layer thickness standard	layer thickness
6.7 Index of Refraction		
6.7.1	refractometer for optical materials	refractive index, *n*
6.7.2	refractive index of solids	refractive index, *n*

Structure of the CCL and working groups

How far the light shines

Principal Techniques	CCL-K1	CCL-K2	CCL-K3		CCL-K4	CCL-K5		CCL-K6	CCL-K7	CCL-K8
	gauge block	length bar	poly	gau.	diameter	ball	step	2D CMM	linescale	surf tex.
Realizing the Metre definition										
Interferometry	2	2			2	2		2	2	1
Wavelengths in air	2	2			2	2		2	2	1
Gauge Issues										
Temperature of Gauge	1	2			2	2		2	2	1
Mounting & Aligning	1	2	2		2	2		2	2	1
Wavefront Probing										
Reflection Phase Effects	2	1								
Wringing	2	1								
Mechanical Probing										
Stylus contacting at surface, 1-D					2	1	2	1		2
Bi-directional probing for size					2		2			
Probing for 3-D center coordinates						2		2		
Image Probing										
Sensing Line Centres									2	
Angle Metrology										
Measuring small angles (autocoll.)			1	2						
Large Angle Gen: Circle Dividers			2	1				1		
Small Angle Gen: SineBar, CircDiv.				2						
Formal mathematical processing of data sets										
ISO parameter extraction										2
Form Metrology										
Flatness										1
Roundness					1					
Thread, Gear Profile										
3-D Surface										1

SIM MWG perspective

SIM MWG Perspective

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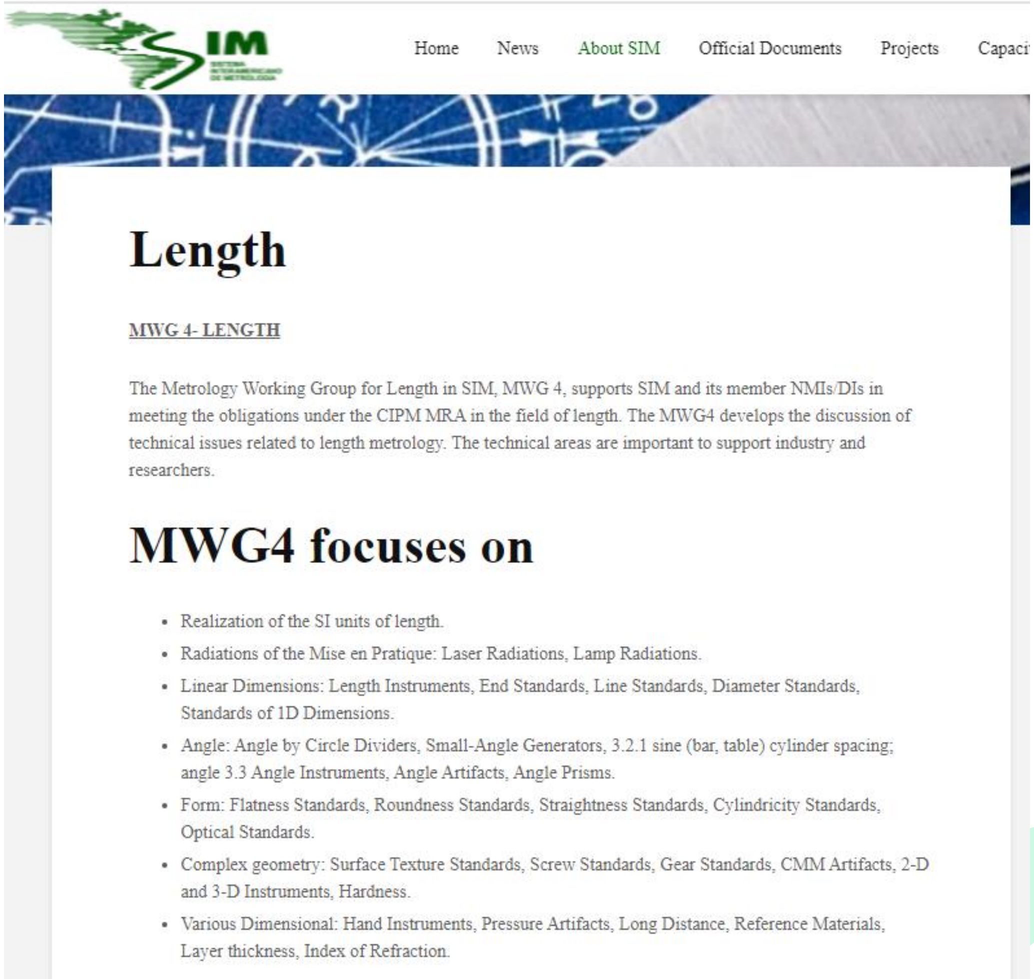

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Length

MWG 4- LENGTH

The Metrology Working Group for Length in SIM, MWG 4, supports SIM and its member NMIs/DIs in meeting the obligations under the CIPM MRA in the field of length. The MWG4 develops the discussion of technical issues related to length metrology. The technical areas are important to support industry and researchers.

MWG4 focuses on

- Realization of the SI units of length.
- Radiations of the Mise en Pratique: Laser Radiations, Lamp Radiations.
- Linear Dimensions: Length Instruments, End Standards, Line Standards, Diameter Standards, Standards of 1D Dimensions.
- Angle: Angle by Circle Dividers, Small-Angle Generators, 3.2.1 sine (bar, table) cylinder spacing; angle 3.3 Angle Instruments, Angle Artifacts, Angle Prisms.
- Form: Flatness Standards, Roundness Standards, Straightness Standards, Cylindricity Standards, Optical Standards.
- Complex geometry: Surface Texture Standards, Screw Standards, Gear Standards, CMM Artifacts, 2-D and 3-D Instruments, Hardness.
- Various Dimensional: Hand Instruments, Pressure Artifacts, Long Distance, Reference Materials, Layer thickness, Index of Refraction.

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Thanks!

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